Lessons from DØ

Markus Wobisch, Louisiana Tech University

February 8, 2010

(my) Lessons from DØ

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(some of) (my) Lessons

from DØ

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(some of) (my) Lessons

from DØ (... and CDF)

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Lessons … what lessons?

- What are “the lessons”?
  → too early to ask!
  → **$dN_{publications}$ / dt is still strongly increasing**
  → … and this is already one lesson: don’t expect too much too soon

- Large number of observables measured in CDF/D0 QCD working groups

- This talk covers a few which are suited for **precision phenomenology**

- Subjective selection of topics / not comprehensive / but **detailed**

- Use opportunity to discuss aspects which can not be discussed during overview/summary plenary talks at conferences, and neither during short parallel session talks dedicated to a single analysis

Outline

- **Jets:**
  Variables, Algorithms, Calibration
- **Inclusive Jets:**
  Measurement, Radius Dependence, α_s
- **Dijets:**
  Mass, Angular Distributions, New Physics
- **Beyond 2→2 scattering**
  Dijet Azimuthal Decorrelations, Multi-Jet Ratios

The Observable

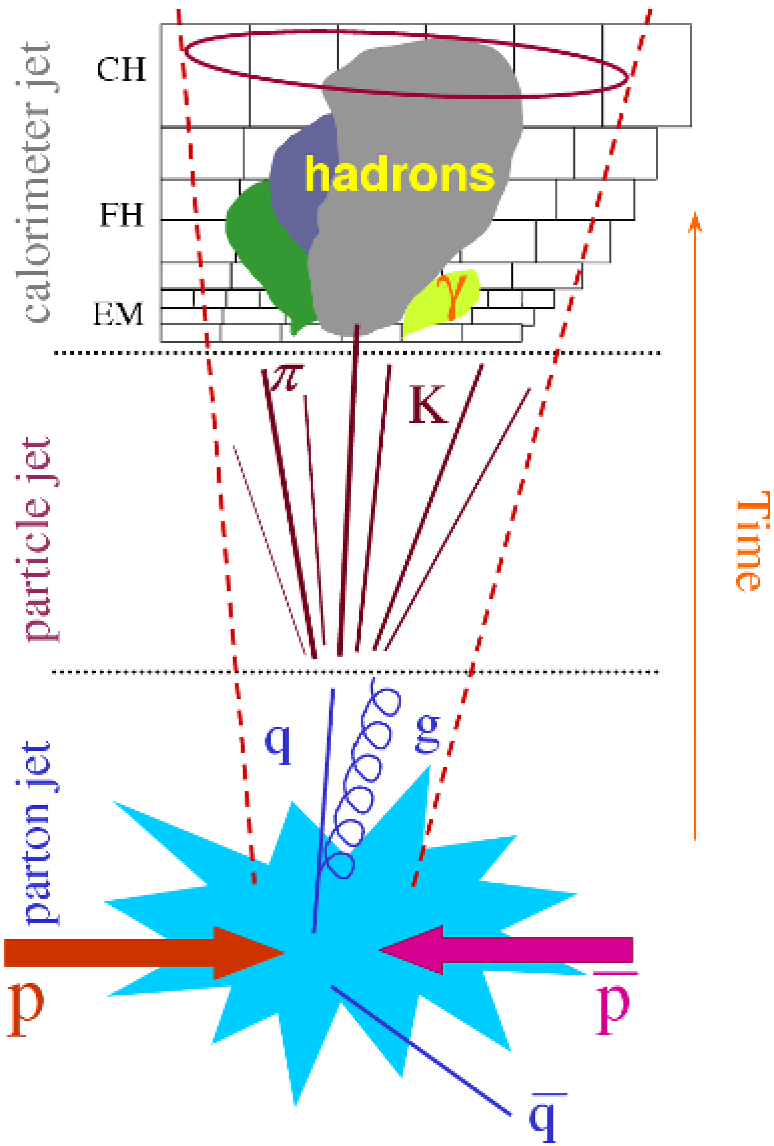
Jets

Comparing theory to data

from the CM frame to the detector

Jet variables

Parton-, Hadron-, Detector- “Jets”



- Use Jet Definition to relate Observables defined on Partons, Particles, Detector

- Direct Observation: Energy Deposits / Tracks

- Stable Particles (=True Observable)

- Idealized: Parton-Jets

  no Observable (color confinement)

  but: quantity predicted in pQCD

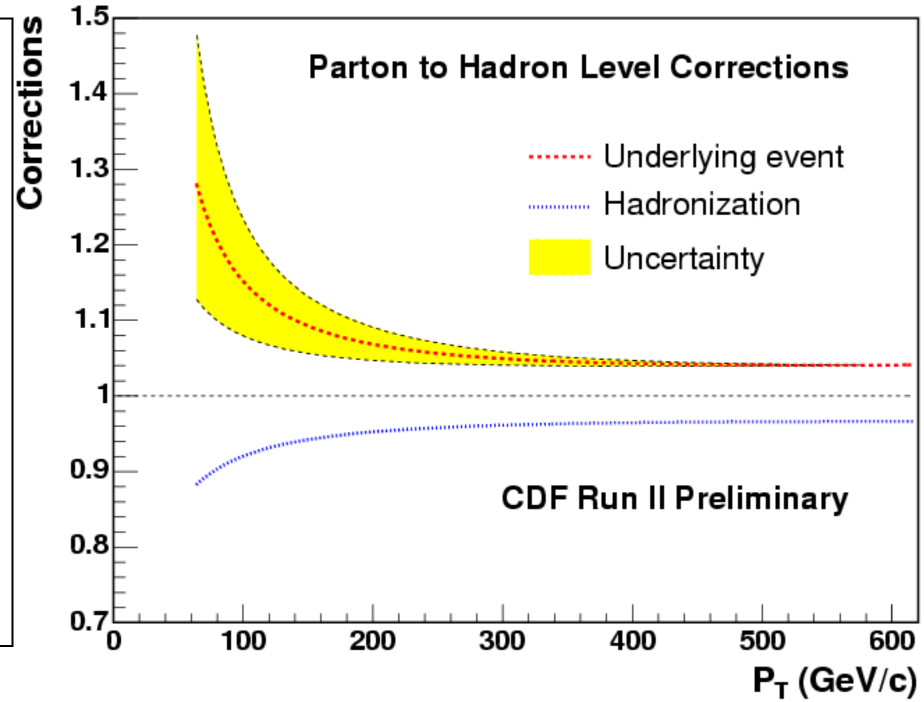
From Particle to Parton Level

- Measure cross section for pp-bar → jets (on "particle-level")
  Corrected for experimental effects (efficiencies, resolution, …)

Use models to study effects of **non-perturbative processes** (PYTHIA, HERWIG)

- **hadronization correction**
- **underlying event correction**

CDF study for cone R=0.7 for central jet cross section



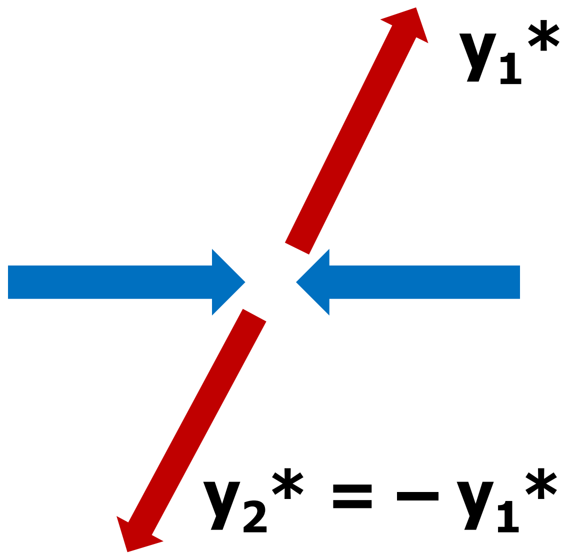
→ Apply this correction to the pQCD calculation
→ used in current MSTW/CTEQ PDF analyses
→ First time consistent theoretical treatment of jet data in PDF fits

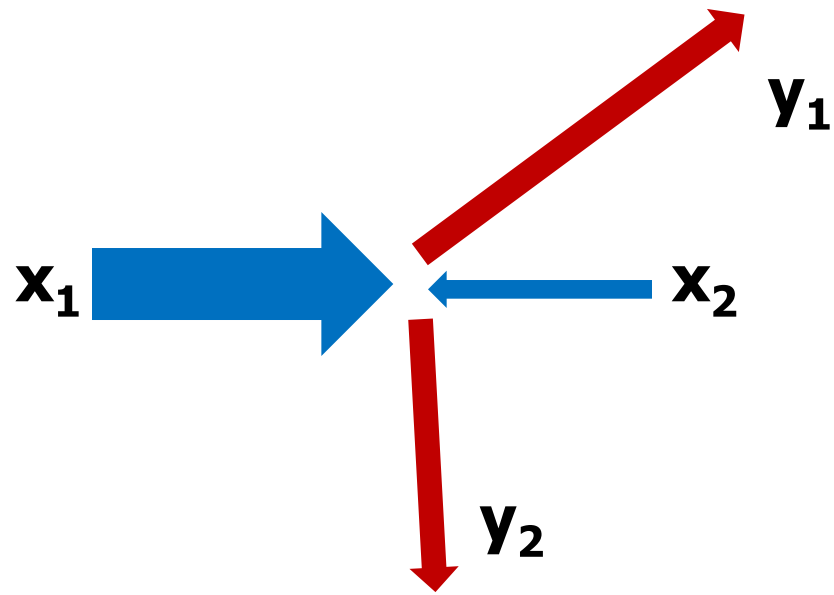
New in Run II !!!

Dijets in CM frame and detector

The physics:
in the dijet CM frame (*)

The observation:
in the lab / detector frame





$$\mathbf{y^* = \tfrac{1}{2}\,|y_1 - y_2|} \quad = \tfrac{1}{2}\,|y_1^* - y_2^*| = |y_1^*| = |y_2^*|$$

$$\mathbf{y_{boost} = \tfrac{1}{2}\,(y_1 + y_2)} \quad = \tfrac{1}{2}\log(x_1/x_2)$$

Dijet Production

Described by eight variables – for example:

1. Dijet Mass Mjj
2. $y^* = \frac{|y_1 - y_2|}{2}$ or: $\chi_{\mathrm{dijet}} \equiv \exp(2y^*)$
3. $y^{\mathrm{boost}} = \frac{y_1 + y_2}{2}$
4. $\Delta\phi = |\phi_1 - \phi_2|$
5. p_{T2}/p_{T1}
6. M/E (jet1)
7. M/E (jet2)
8. Overall rotation in azimuthal angle

features of 2→2 process

PDFs

"hard" higher-order effects

"soft" higher-order effects

irrelevant in unpolarized pp-bar (no reference axis)

Jet Algorithms

IR / collinear safety

Cone jet algorithms

Successive recombination algorithms

IR/collinear safety for observables

Infrared Safety:

→ Adding a soft particle (with E→0) to the final state
does not change the value of the observable

Collinear Safety:

→ Replacing a final-state particle by two collinear particles
(which share the energy of the original particle)
does not change the value of the observable

Remark:

→ These definitions refer only to the observable,
not to a calculation

Wrong to say: "The observable is not infrared safe at NNLO"

Correct: "It's not IR safe! … and at NNLO you will notice that."

Cone Algorithms – a brief history

- Sterman/Weinberg (1977): 1st proposal for a jet algorithm
  → slide a cone to maximize energy / pT flow

- UA1 cone algorithm – obviously IR unsafe
- Snowmass Accord: improvement → iterative cone algorithm used in Run I by CDF/D0 (CDF added "ratcheting", undocumented)
- LEP, HERA: iterative midpoint algorithms
- Run II workshop → "Run II cone" iterative midpoint algorithm used by D0 (with minor modifications)
- Run II CDF: "searchcone algorithm" to avoid "dark towers"
  → introduces new IR unsafety → CDF goes back to Run II cone

30 years after 1st proposal:

- G. Salam, G. Soyez: **SIScone** → 1st IR/collinear safe cone algorithm!!

Successive Recombination Algorithms

- One problem with cone algorithms (even with SIScone) remains:
  Treatment of overlapping proto-jets ("split/merge")
  Although well-defined, and (for SIScone) IR safe
  → still ugly feature (introducing additional parameters)

Avoided by successive recombination algorithms / all: IR and collinear safe

- JADE algorithm (clustering in mass → "phantom jets")
- k_T algorithm (clustering in relative k_T)
- Cambridge/Aachen algorithm (clustering in angle)
- Anti-k_T algorithm (clustering in inverse relative k_T)

→ Step-by-step procedure: result is defined at any intermediate step

→ **Today: generally preferred (CDF in Run II: k_T algorithm)**

The Experiment

Jet Energy Calibration

Correlations of uncertainties

What do we calibrate?

Jet Energy Calibration

What shall we calibrate?

Jets for a given algorithm?

Restricted to single algorithm
for fixed parameter(s)

Further algorithms/parameters:
redo whole effort

Does not (easily) give correlations
between the uncertainties for
different algorithms/parameters

Does not allow to measure
internal jet structure

→ But: Can lead to higher precision

Detector objects?

(cells, clusters, towers)

→ Easier usage:

Once detector objects are
calibrated:
run any algorithm w/ any
parameter setting over
calibrated objects

→ Get uncertainty correlations
between results for different
algorithms / parameter(s)

→ Maybe less precision(?)

Jet Energy Calibration

- Calibration for cone jets with R=0.5 / 0.7
- based on data (missing ET projection method)
- Uncertainties are divided into 48 uncorrelated sources

→ Huge effort

→ Great result: 1% (most precise jet energy calibration at a hadron collider)!

→ Due to limited person-power:
Not able to repeat this effort for other jet algorithm(s)
  - No k_T, C/A, SIScone results from D0

Inclusive Jets

measurements

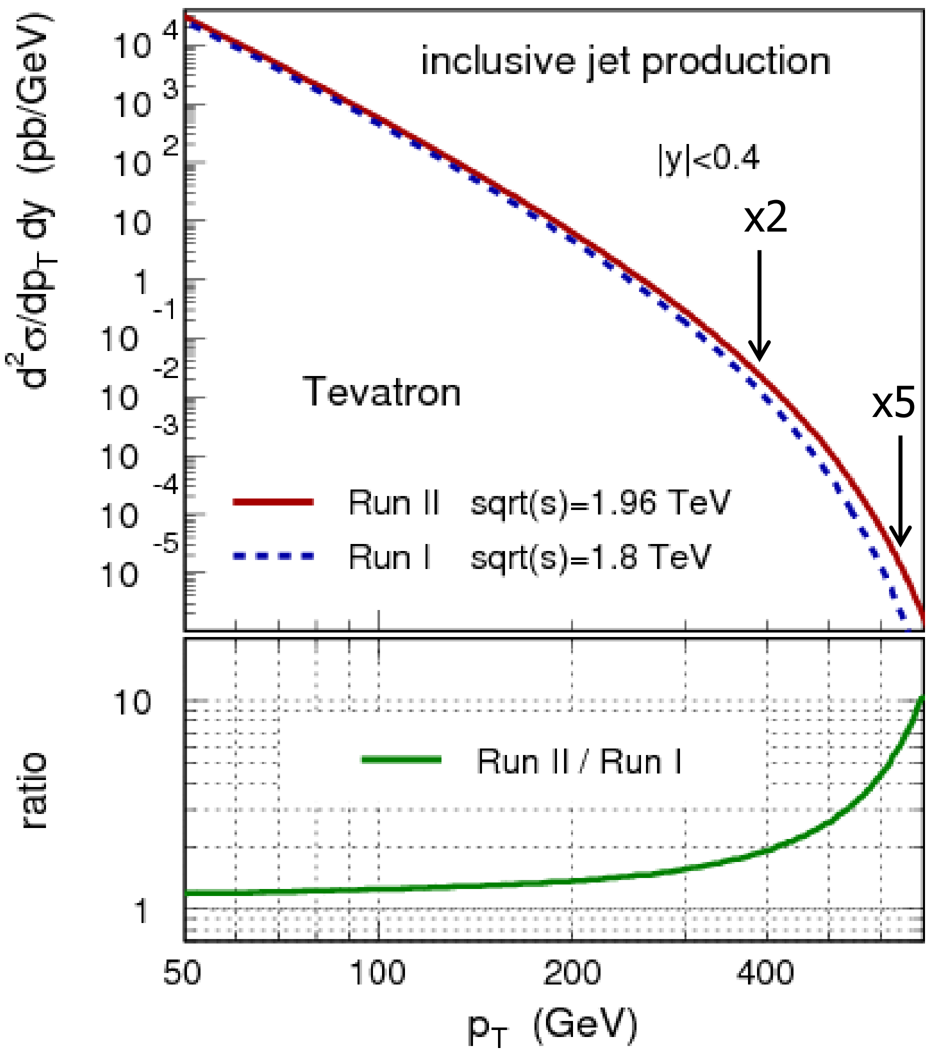
PDF sensitivity

Jet algorithm dependence

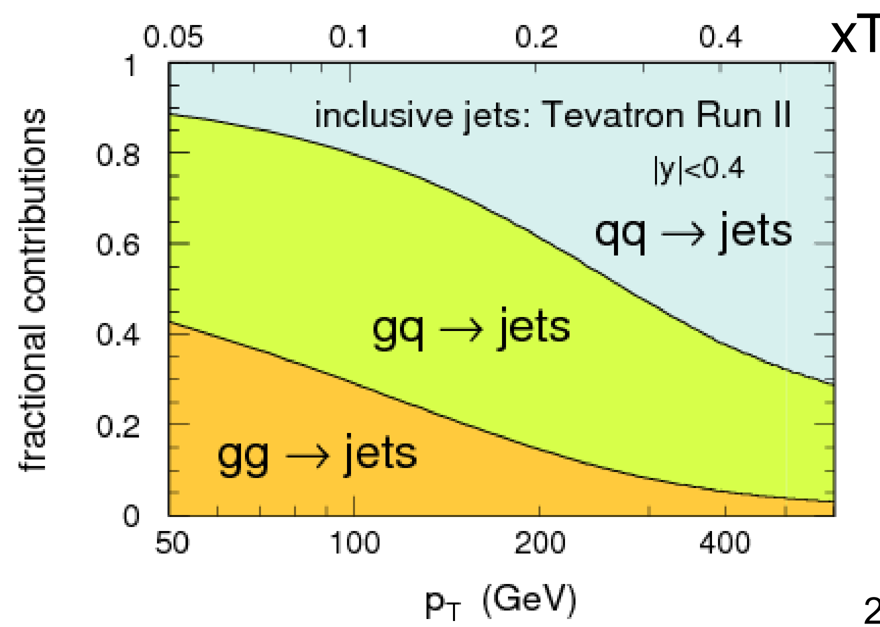
Jet radius dependence (vs. NLO pQCD)

α_s determination (& limitations)

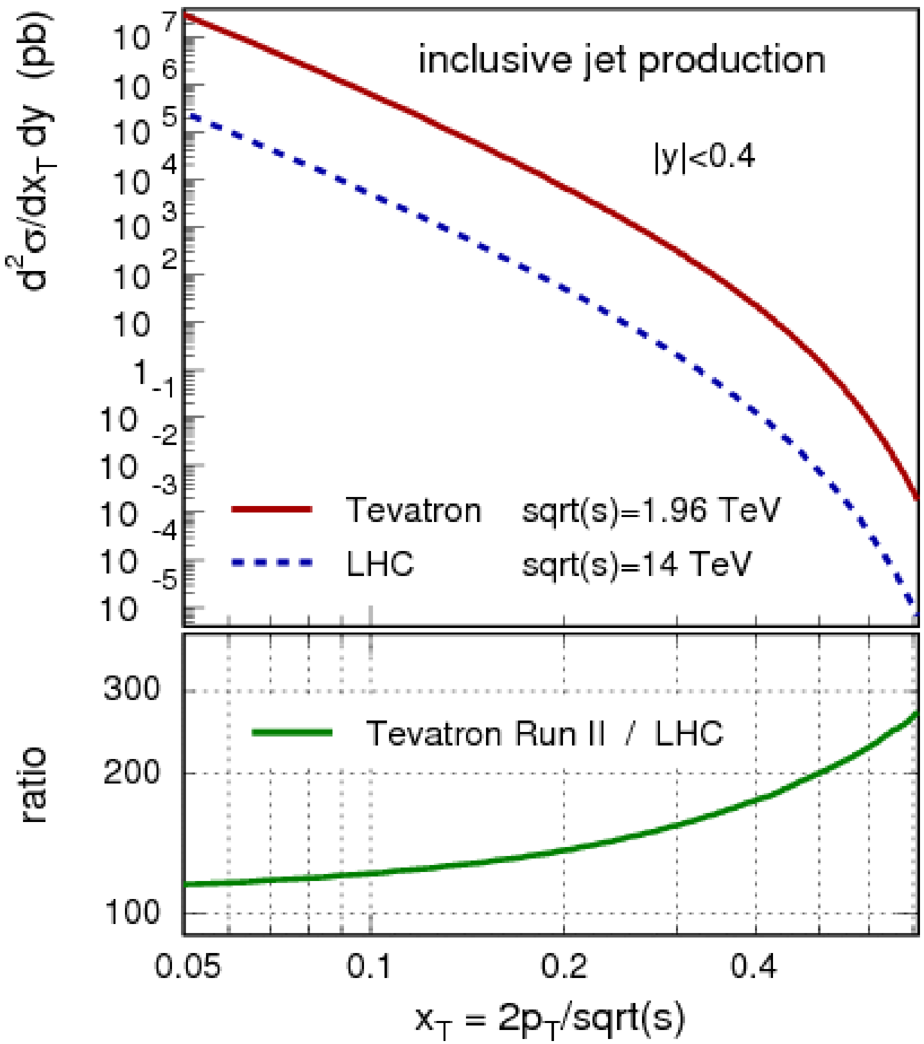
Inclusive Jet Production



- Run II: Increased x5 at pT=600GeV
  → sensitive to "New Physics":
  Quark Compositeness,
  Extra Dimensions, …(?)…
- Theory @NLO is reliable (10%)
  → sensitivity to PDFs
  → unique: high-x gluon



Inclusive Jets: Tevatron vs. LHC



PDF sensitivity:

→ compare jet cross section at fixed

$x_T = 2\ p_T\ /\ \mathrm{sqrt}(s)$

Tevatron (ppbar)

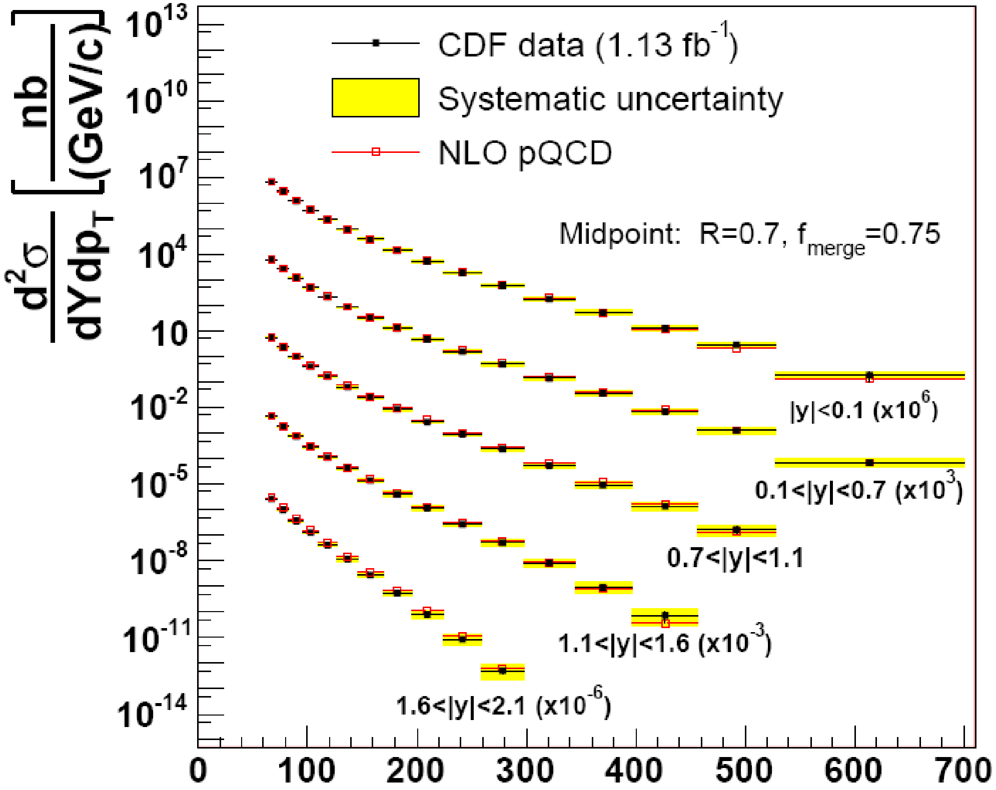
>100x higher cross section @ all x_T

>200x higher cross section @ x_T >0.5

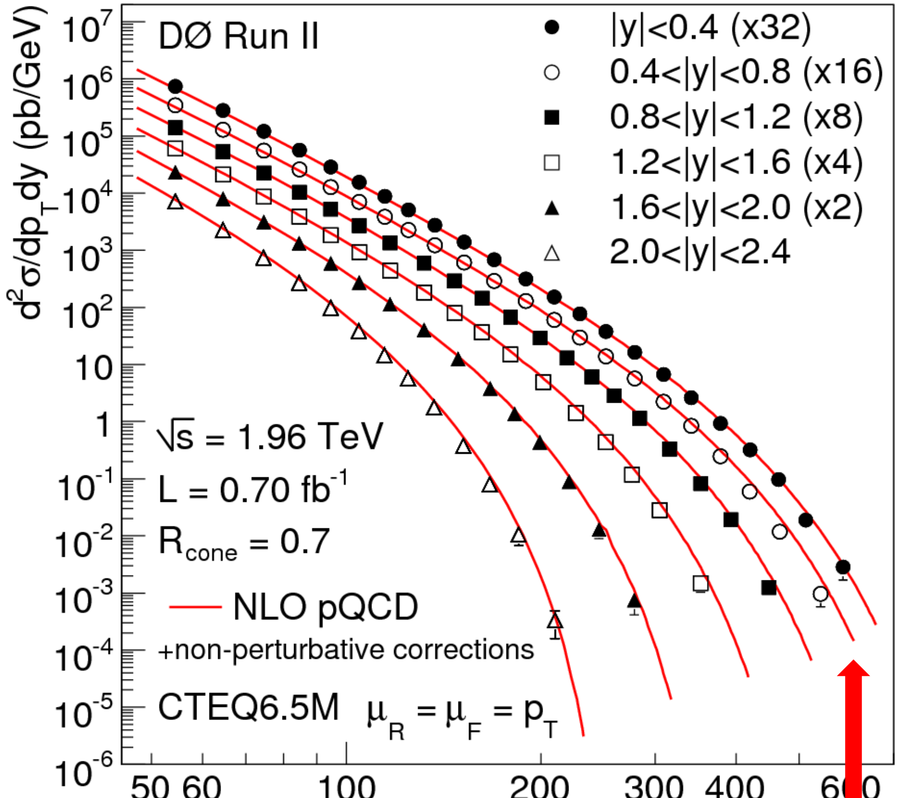
LHC (pp)

- need more than 2400 fb^{-1} luminosity to improve Tevatron@12 fb^{-1}
- more high-x gluon contributions
- but more steeply falling cross sect. at highest p_T (=larger uncertainties)

Inclusive Jets



Phys. Rev. D 78, 052006 (2008) **p_T (GeV)**



Phys. Rev. Lett. 101, 062001 (2008) **p_T (GeV)**

benefit from:
- high luminosity in Run II
- increased Run II cm energy → high p_T
- hard work on jet energy calibration

steeply falling p_T spectrum:
1% error in jet energy calibration
→ 5—10% (10—25%)
central (forward) x-section

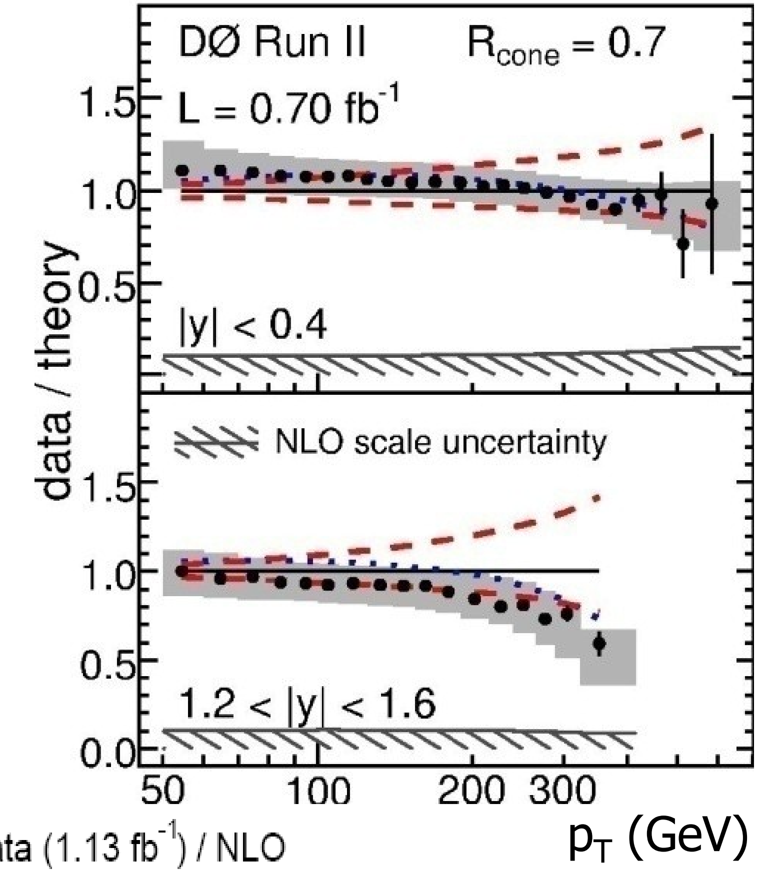
Inclusive Jets

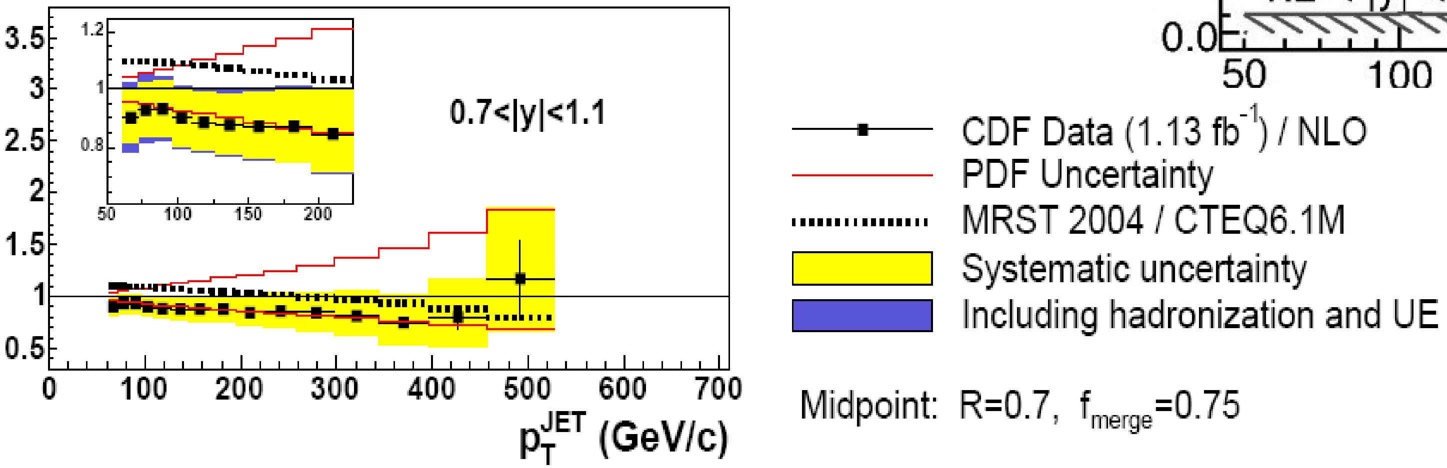
- high precision results
- consistency between CDF/D0
- well-described by NLO pQCD
- experimental uncertainties:
  smaller than PDF uncertainties!!

→ sensitive to distinguish between PDFs

data are used in PDF fits:

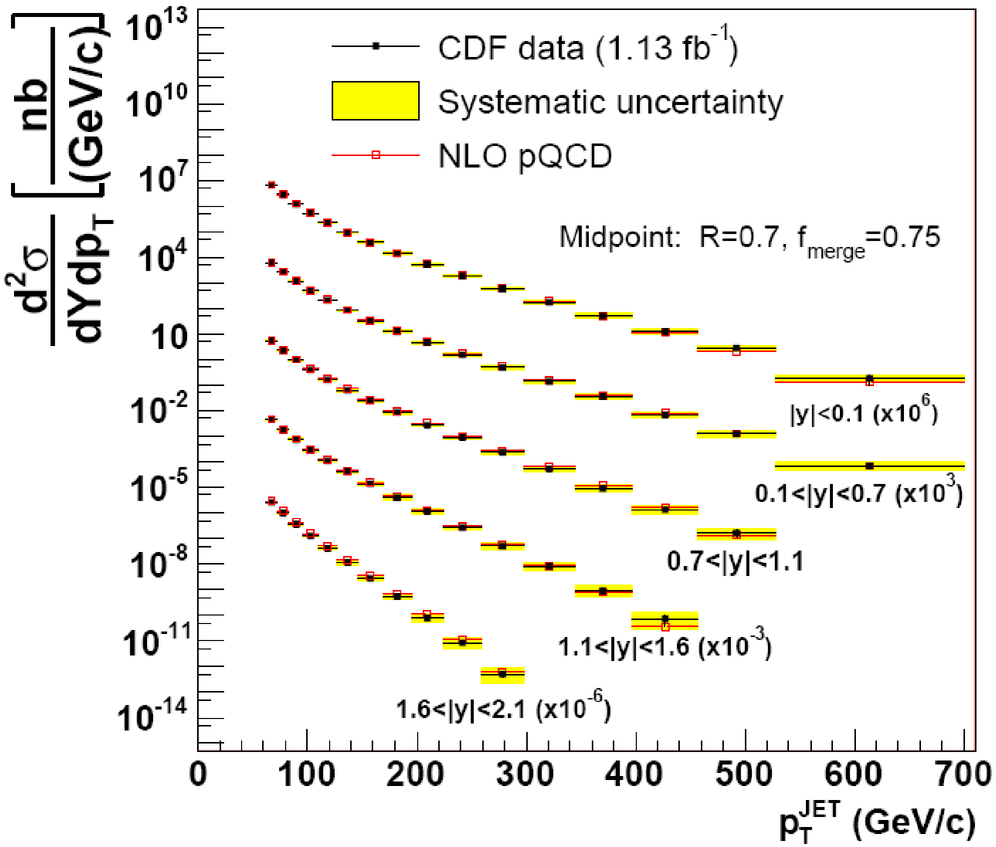
- included in MSTW2008 PDFs
- at work: forthcoming CTEQ PDFs

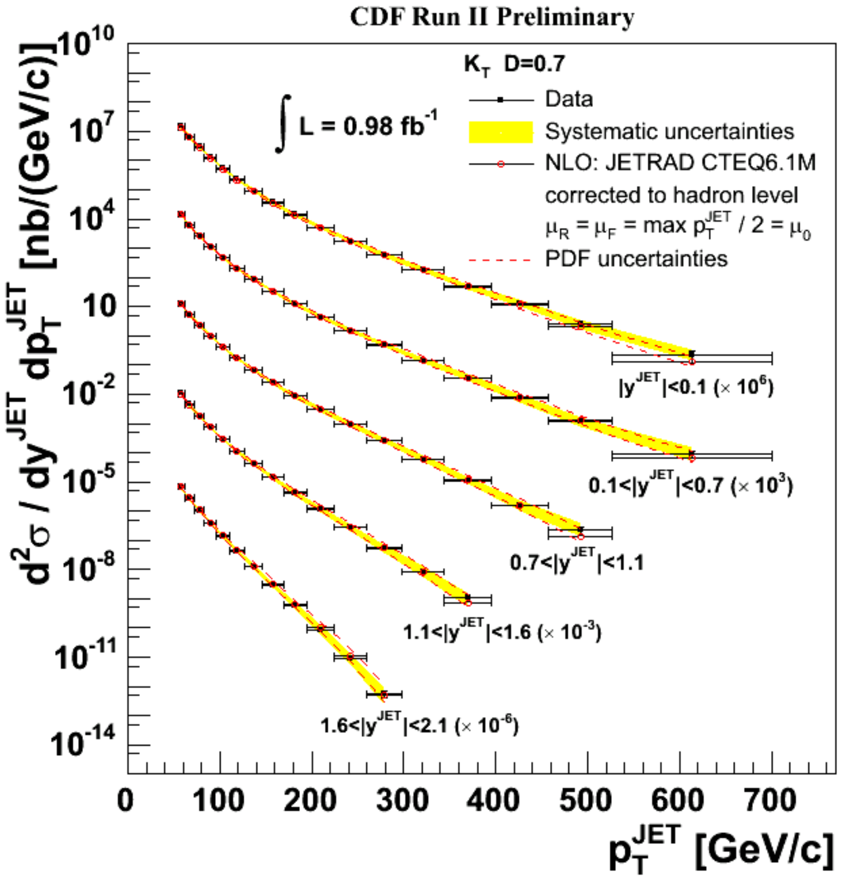




Inclusive Jets
Cone and k_T Algorithms

2007/2006 results with large rapidity coverage for 1fb-1

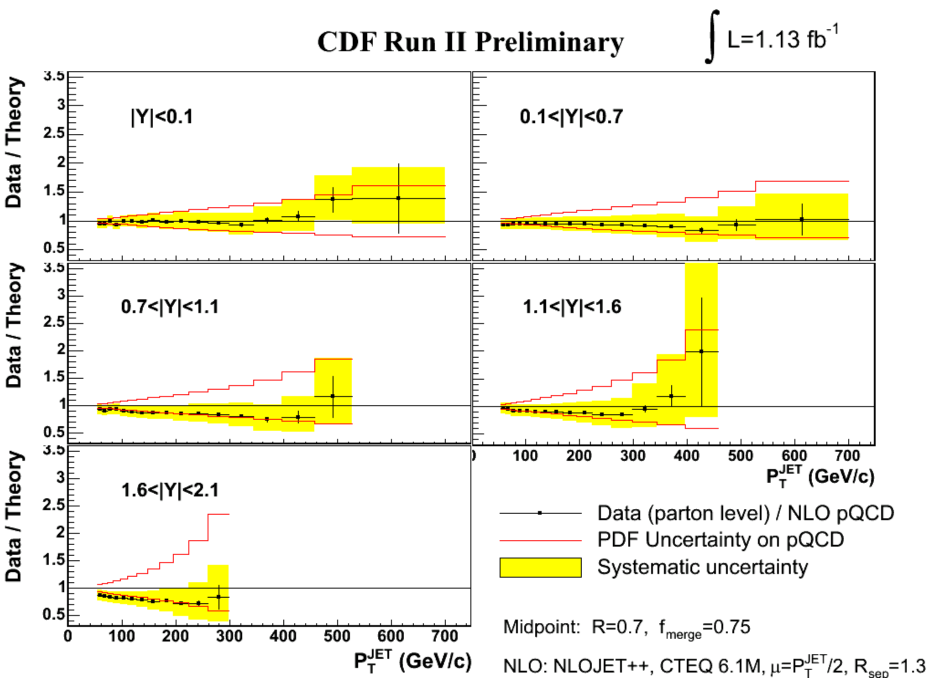




Midpoint Cone Algorithm

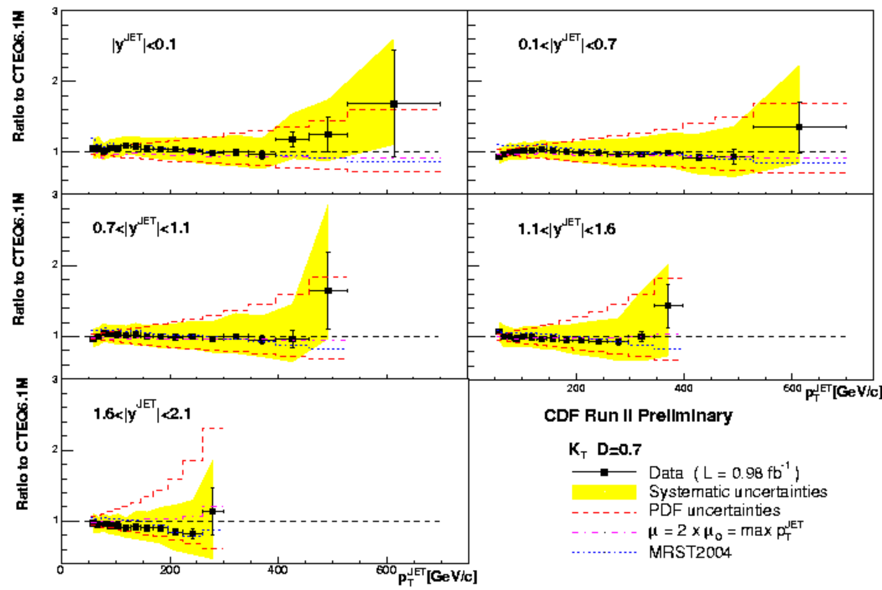
k_T Algorithm

Inclusive Jets
Cone and k_T Algorithms



Midpoint Cone Algorithm

Phys. Rev. D 75, 092006 (2007)



k_T Algorithm

Interpretations of CDF cone and k_T jet results are consistent
For more quantitative statement → study the ratio

Comparing k_T vs. cone jets

CDF inclusive jets for k_T and cone:

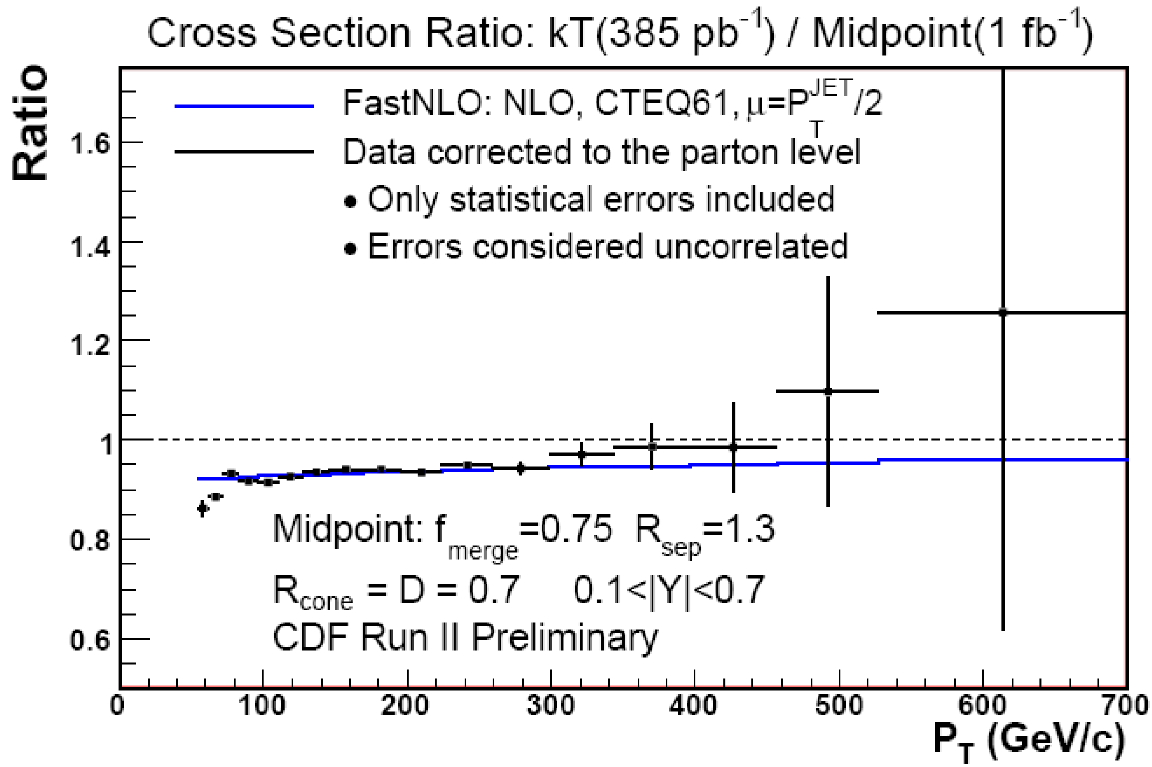
S. Ellis et al, Prog.Part.Nucl.Phys.60:484-551,2008

Compare ratio of inclusive jet cross section for k_T and cone jet algorithm

In

- data
- theory

(as the ratio of NLO calculations for cross sections)



"errors are considered to be uncorrelated" → correlation is not known!

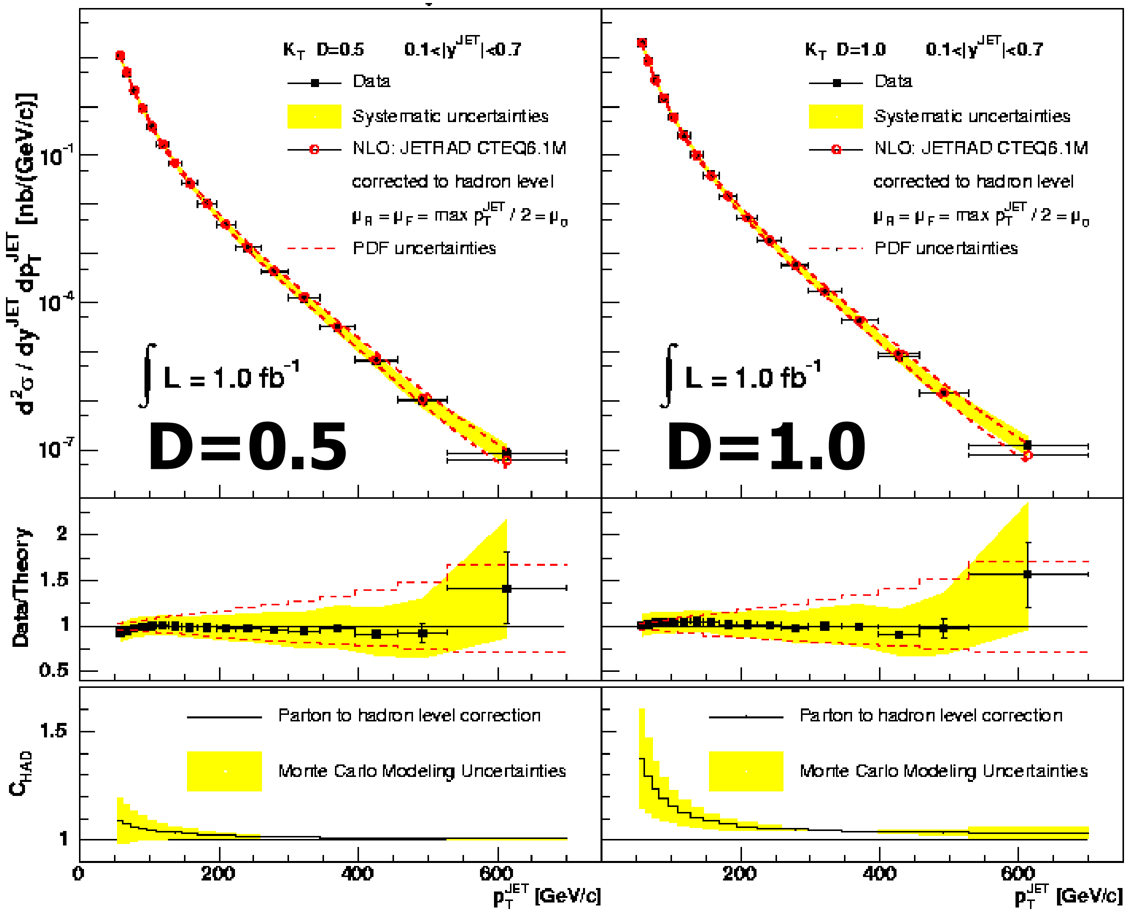
theory here:

ratio of NLO cross sections → only LO prediction for the ratio

Radius Dependence of Jet Cross Sections

Jet cross section depends on radius in jet definition
→ Important testing ground

Phys. Rev. D 75, 092006 (2007)



CDF: radius dependence for incl. jets (k_T jet algorithm) for D (=radius) parameter D = 0.5, 0.7, 1.0

→ Results for each D value are compared to NLO pQCD calculation + non-pert corr.

→ agreement for all D values

(similar analysis in DIS by ZEUS)

→ For quantitative test:
study **ratios** and compute prediction at true NLO (using 3-jet NLO)

Radius Dependence of Jet Cross Sections @NLO

Ratio of cross sections: $$R(D) = \frac{\sigma(D)}{\sigma(D_0)} = 1 + c_1\alpha_s + c_2\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

- Jet cross section at **LO** → **no** radius dependence
- Jet cross section at **NLO** → **LO** contribution to radius dependence

$$\frac{[\sigma(D)]_{\mathrm{NLO}}}{[\sigma(D_0)]_{\mathrm{NLO}}} = \left[\frac{\sigma(D)}{\sigma(D_0)}\right]_{\mathrm{LO}} = R_{\mathrm{LO}}(D)$$

- Jet cross section at **NNLO** → **NLO** contribution to radius dependence

NNLO calculation not available → missing: 2-loop virtual corrections

→ but: 2-loop virtual correction don't depend on radius (2→2 kinematics)

→ contributions from 2-loop corrections cancel in difference

Use **three-jet NLO calculation** to compute **difference**

→ obtain **NLO** result for ratio:

$$\frac{[\sigma(D) - \sigma(D_0)]_{\mathrm{NLO}}}{[\sigma(D_0)]_{\mathrm{NLO}}} + 1 = \left[\frac{\sigma(D)}{\sigma(D_0)}\right]_{\mathrm{NLO}} = R_{\mathrm{NLO}}(D)$$

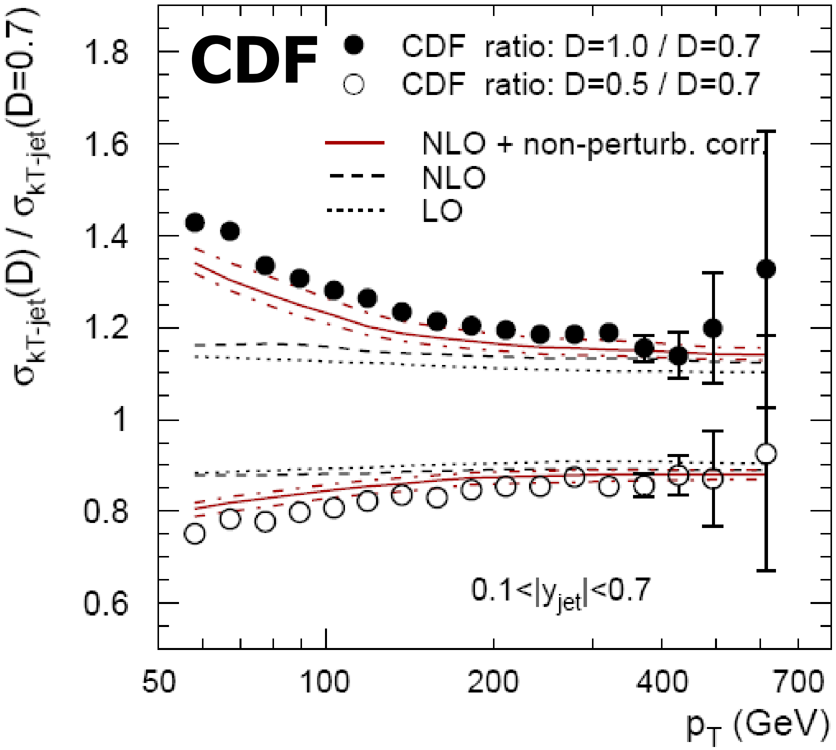
→ use for first NLO study of radius dependence of jet cross sections

Radius Dependence of Jet Cross Sections @NLO

Study cross section **ratios**:

T. Kluge, M.W. – work in progress

(D=1.0/D=0.7) and (D=0.5/D=0.7) and compare with true NLO calculation



scales: mu=p_T (0.5 p_T, 2p_T)

only at highest p_T :

→ agreement at the edge of scale dependence

disagreement at lower p_T :

→ larger radius dependence in data

→ NLO corrections are <20% for Tevatron

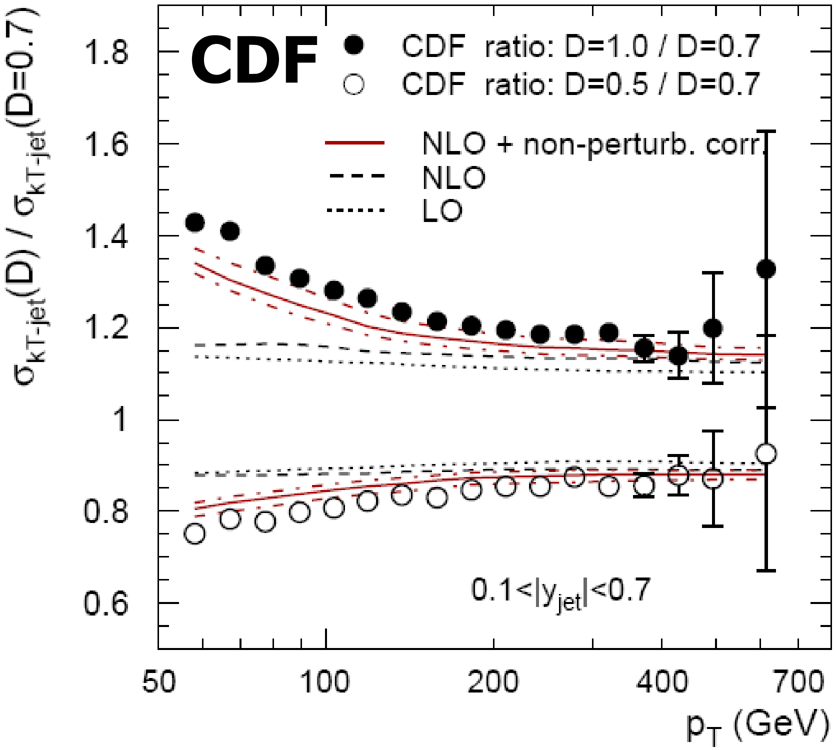
→ most of p_T range: dominated by non-pert. corrections

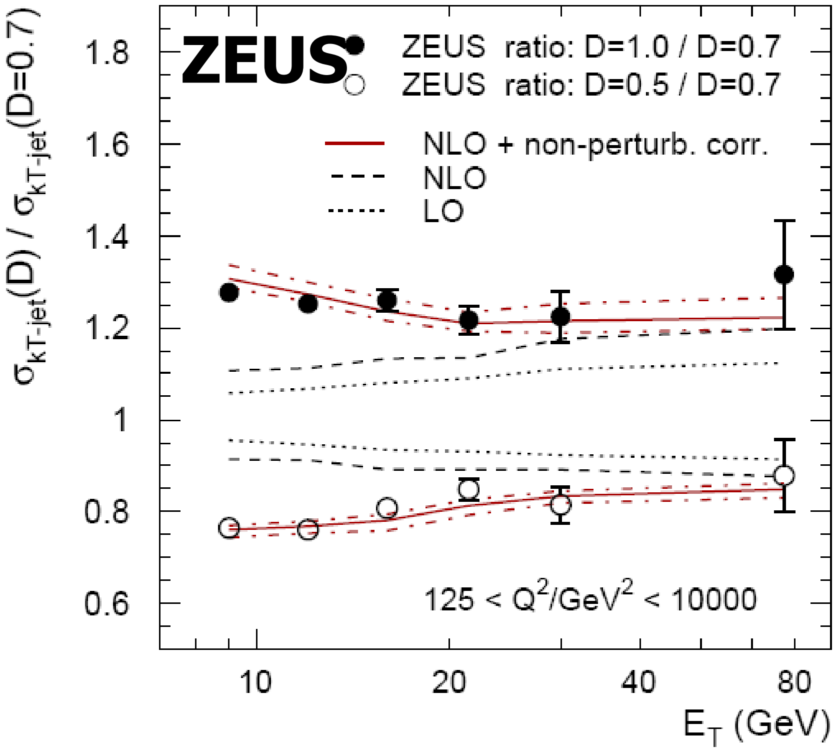
Radius Dependence of Jet Cross Sections @NLO

Study cross section **ratios**:

T. Kluge, M.W. – work in progress

(D=1.0/D=0.7) and (D=0.5/D=0.7) and compare with true NLO calculation





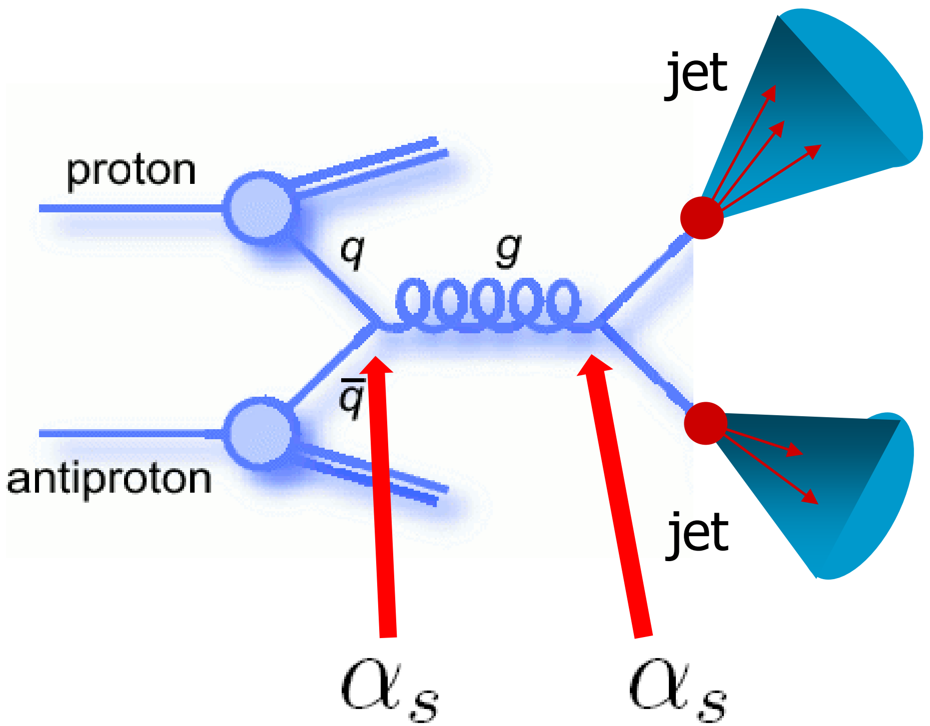
→ NLO corrections are <20% for Tevatron ~60-100% for HERA

→ most of p_T range: dominated by non-pert. corrections

→ HERA data described / Tevatron data not → underlying event???

Strong Coupling Constant

inclusive jet cross section is sensitive to α_s



$$\sigma_{\mathrm{pert}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n \right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

previous CDF result from Run I: PRL88, 042001 (2002)

Strong Coupling Constant

Use MSTW2008NNLO PDFs as input

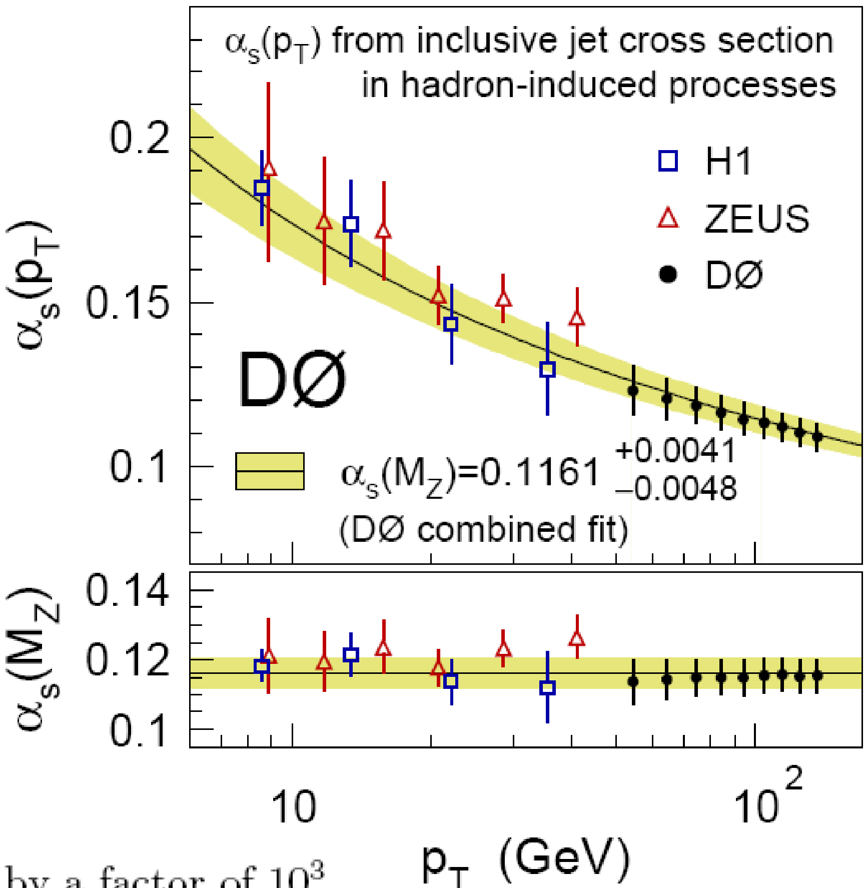
→ Cannot test RGE at p_T >200 GeV (RGE already assumed in PDFs)

→ Exclude data points with $x_{max} \gtrsim 0.25$ (unknown correlation with PDF uncert.)

→ 22 (out of 110) inclusive jet cross section data points at 50<p_T <145 GeV

→ NLO + 2-loop threshold corrections

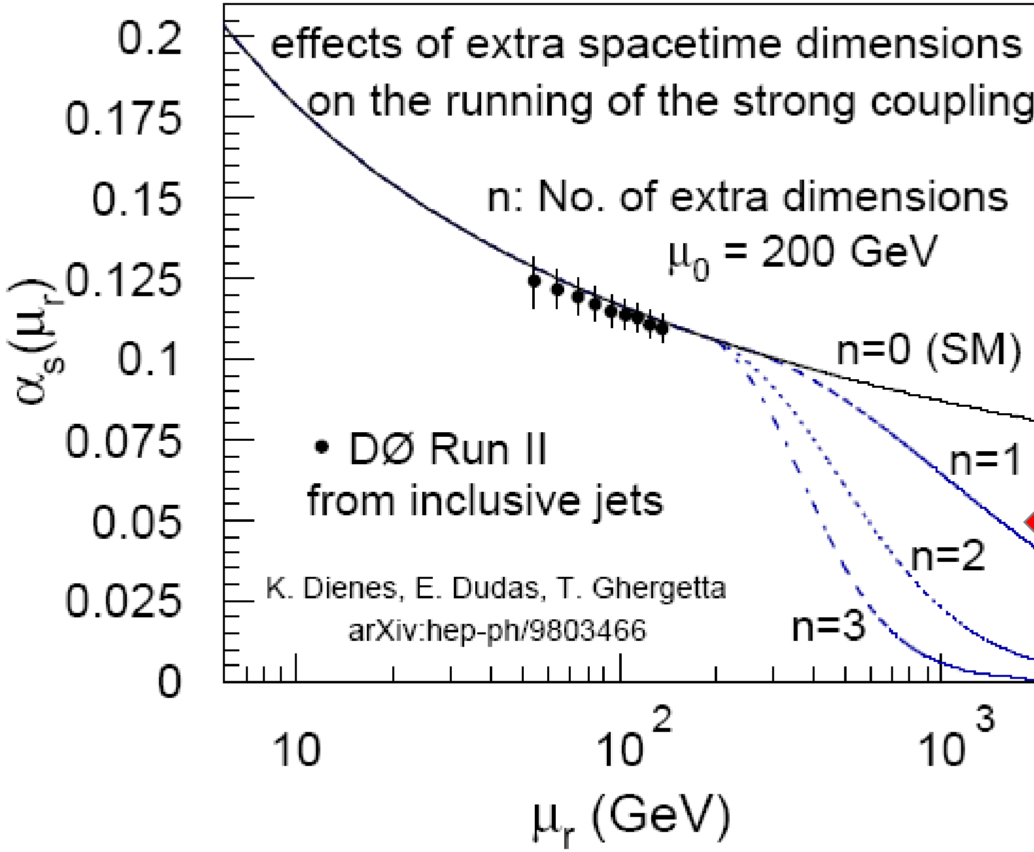
$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$



All uncertainties are multiplied by a factor of 10^3

	Total uncertainty	Experimental uncorrelated	Experimental correlated	Nonperturb. correction	PDF uncertainty	$\mu_{r,f}$ variation
0.1161	$^{+4.1}_{-4.8}$	± 0.1	$^{+3.4}_{-3.3}$	$^{+1.0}_{-1.6}$	$^{+1.1}_{-1.2}$	$^{+2.5}_{-2.9}$

Running of alpha-s (?)



→ so far tested
up to μ_r = 200 GeV

Could be modified
for scales $\mu_r > \mu_0$
e.g. by extra dimensions

here: μ_0 = 200 GeV
and n=1,2,3 extra dim.
(n=0 → Standard Model)

α_s extraction from inclusive jets uses PDFs which were derived assuming the RGE

→ We cannot use the inclusive jets to test the RGE in yet untested region

Lessons from incl. jets (1)

The inclusive jet cross section – double differentially vs. (p_T ,y)

- Consistency between CDF and D0 (and between cone/k_T)
- Traditionally THE measurement to constrain PDFs
  → although triple dijet cross section (p_T,y*,yboost) is more sensitive
- More useful if measured with IR safe jet algorithms
  → if possible successive recombination: k_T, CA, anti-k_T
- this measurement requires
  - best possible energy calibration
    → Calibrate jets / or detector objects?
  - Knowledge of correlations of uncertainties (calibration, resolution) over p_T and rapidity: D0 uses 48 separate sources

Lessons from incl. jets (2)

The inclusive jet cross section – double differentially vs. (p_T,y)

- Important testing ground: Measurement of
  - radius dependence (for given algorithm)
  - Jet algorithm dependence (for given radius)

  → both require correlations of uncertainties between jets for different radii / different algorithms
  → not available for existing CDF / ZEUS measurements
  → easier if energy calibration is done for energy depositions (cells/clusters/towers) not possible if energy calibration
  → correlations must be documented in publications

- Limited sensitivity to alpha-s:
  → no independent test of RGE, since alpha-s extraction requires input from PDFs, which already use alpha-s and the RGE in the evolution.
  → determination restricted to region where RGE was found to be valid

Inclusive Dijets

dijet mass distribution

Angular ratios or angular ratios?

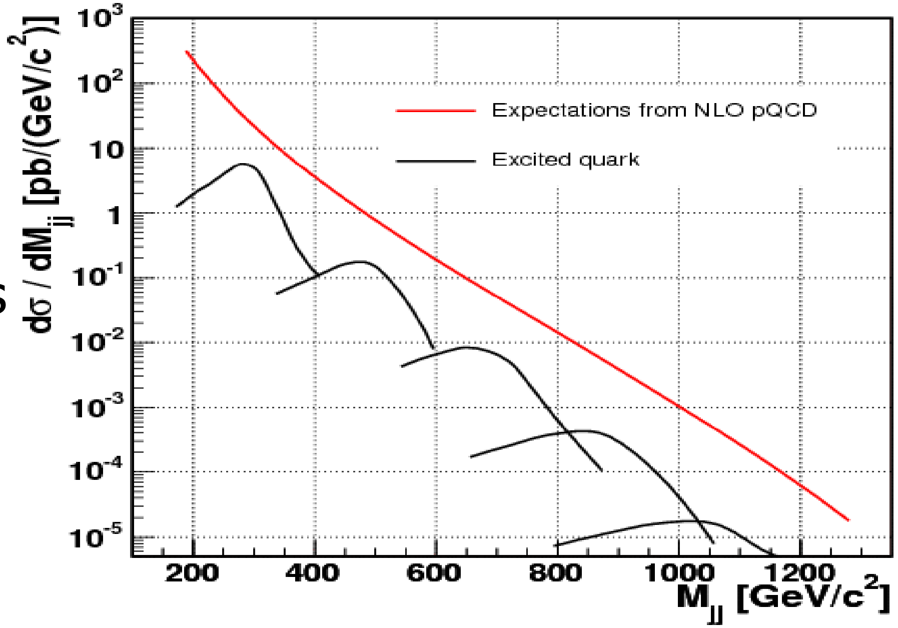
Dijet angular distributions

New Physics limits

Dijet Mass Distribution

central dijet production |y|<1

- test pQCD predictions
- sensitive to new particles decaying into dijets: excited quarks, Z', W', Randall-Sundrum gravitons, color-octet, techni-rho, axigluons, colorons



Dijet Mass Distribution

central dijet production $|y|<1$

- test pQCD predictions
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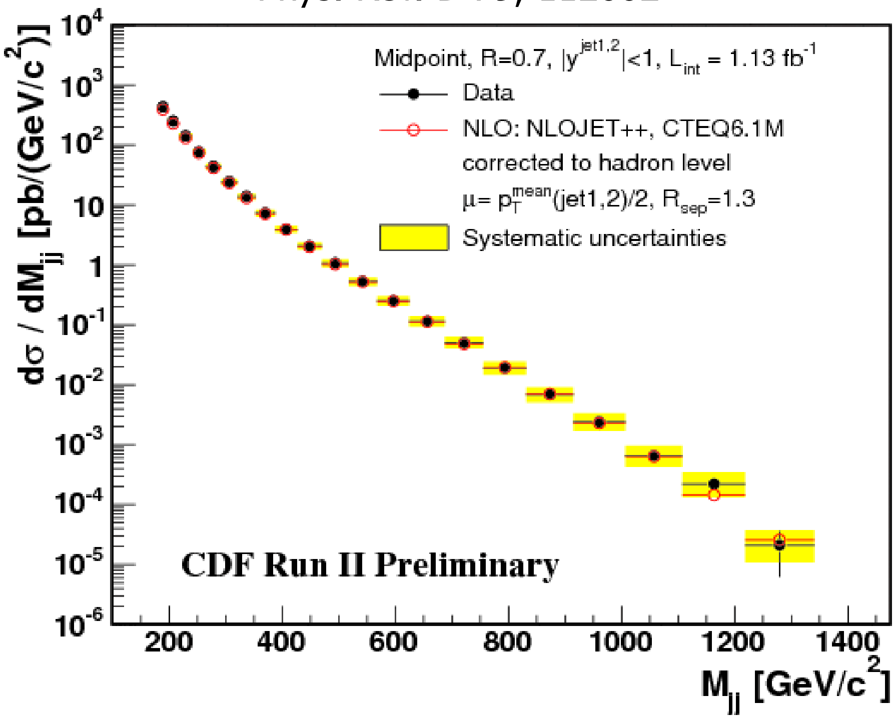
Phys. Rev. D 79, 112002



Dijet Mass Distribution

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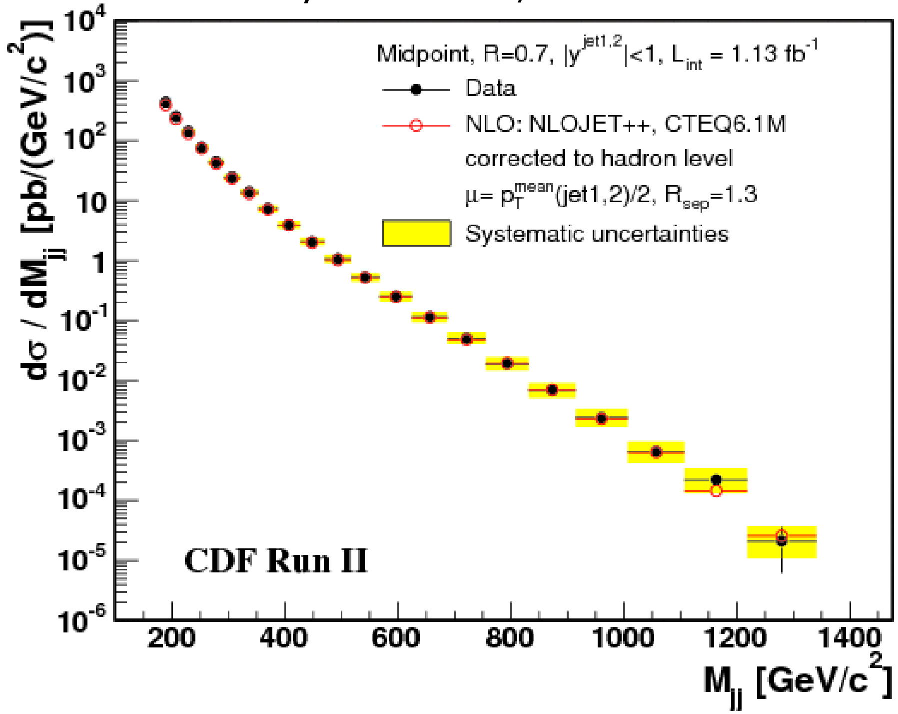
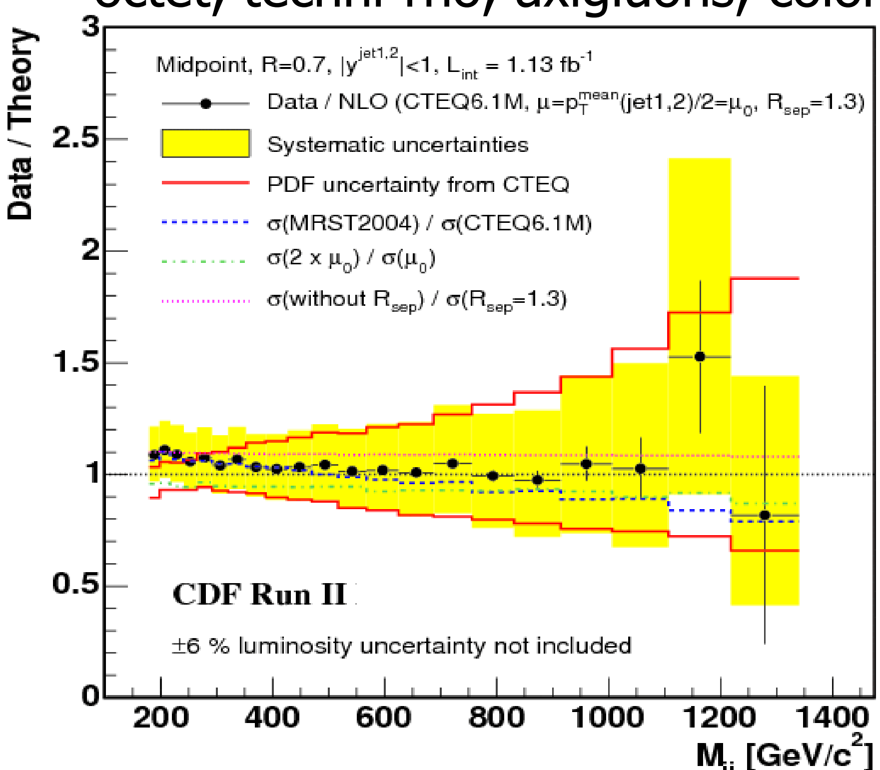
Phys. Rev. D 79, 112002





→ data with Mjj > 1.2 TeV!
→ all described by NLO pQCD

no indications for resonances
→ set limits on new particles

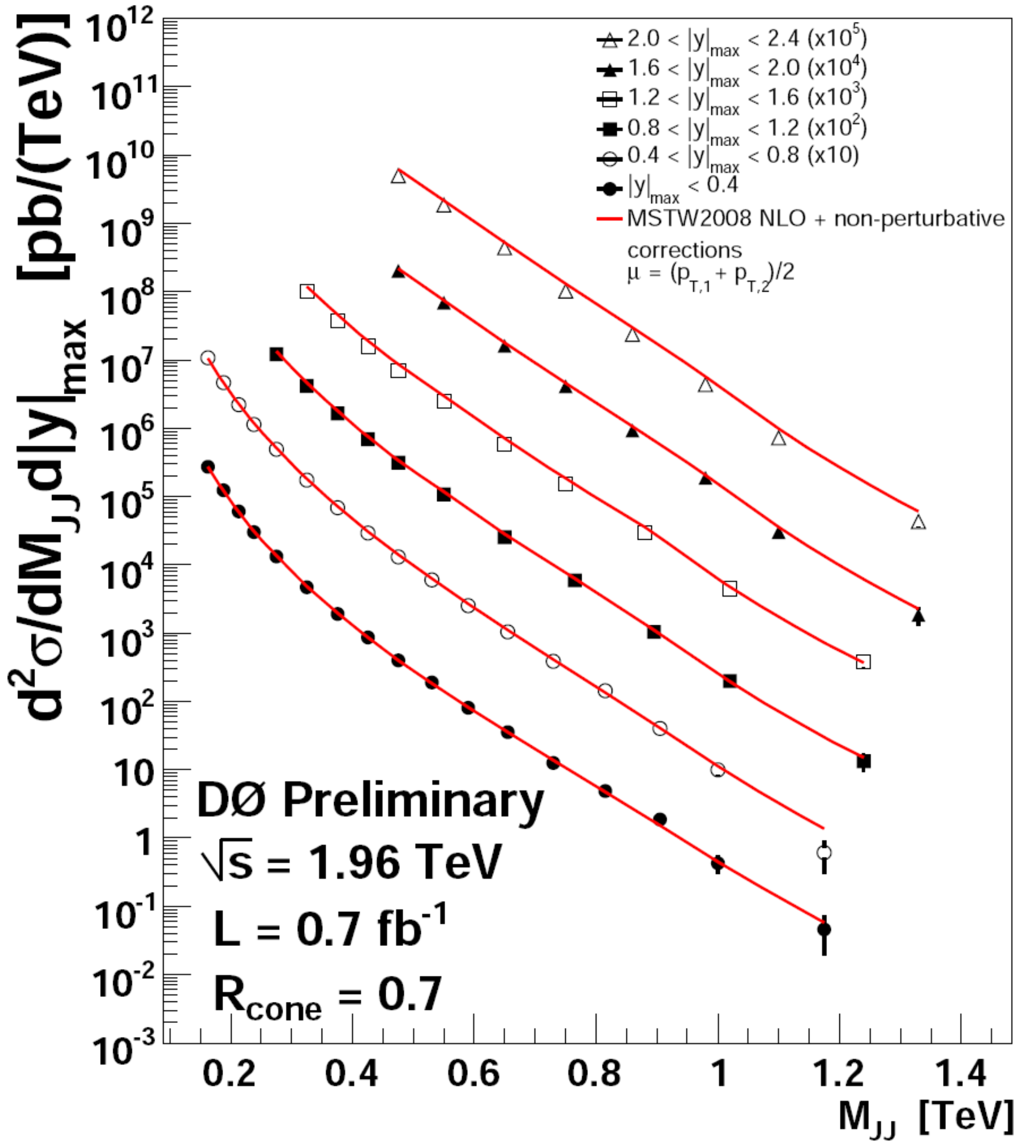
Dijet Mass Spectrum

in six |y|-max regions

0<|y|-max<2.4

Extend QCD test to forward region

→ data with Mjj > 1.2 TeV!
→ described by NLO pQCD

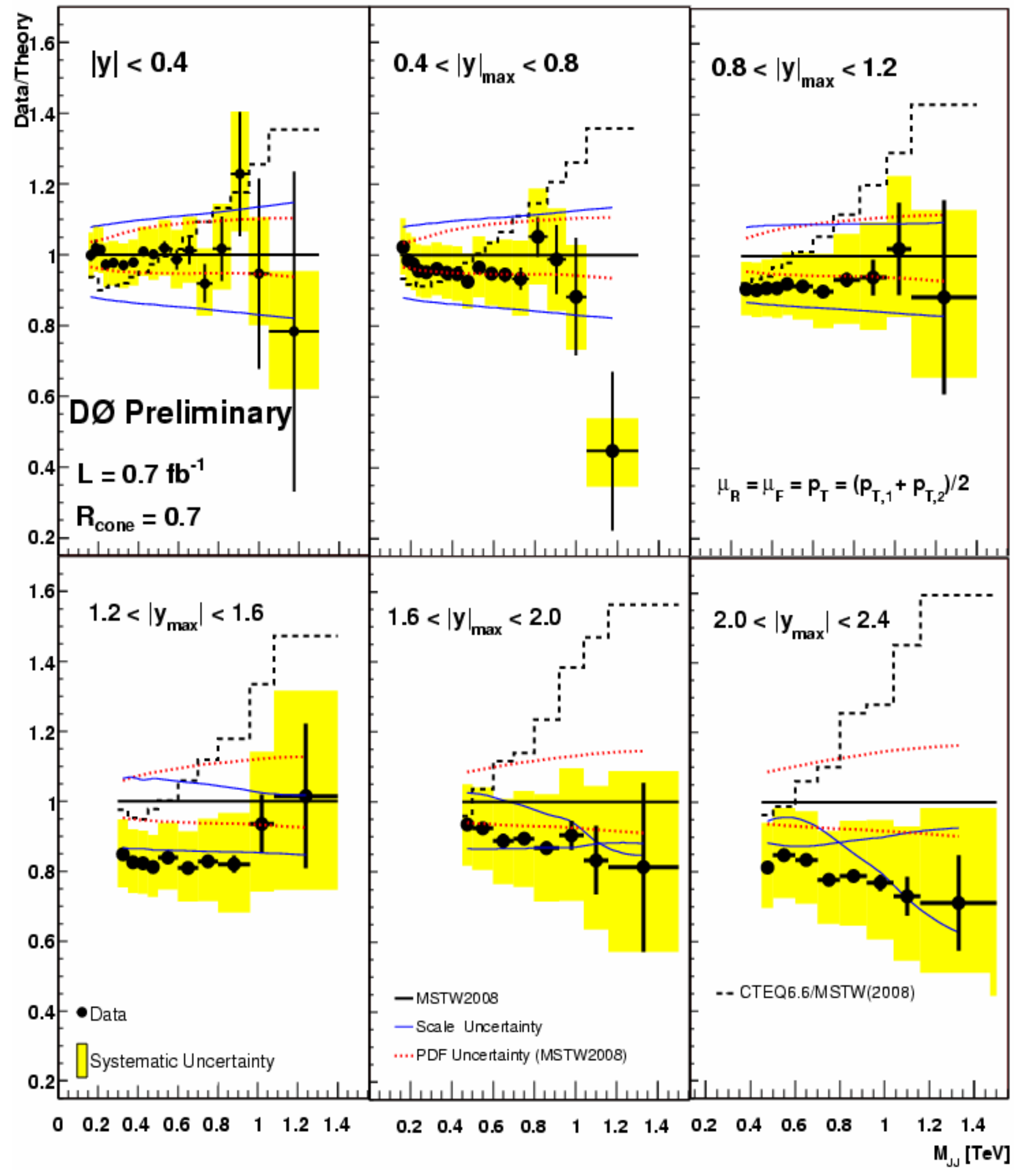


Dijet Mass Spectrum

in six |y|-max regions

0<|y|-max<2.4

Extend QCD test to forward region



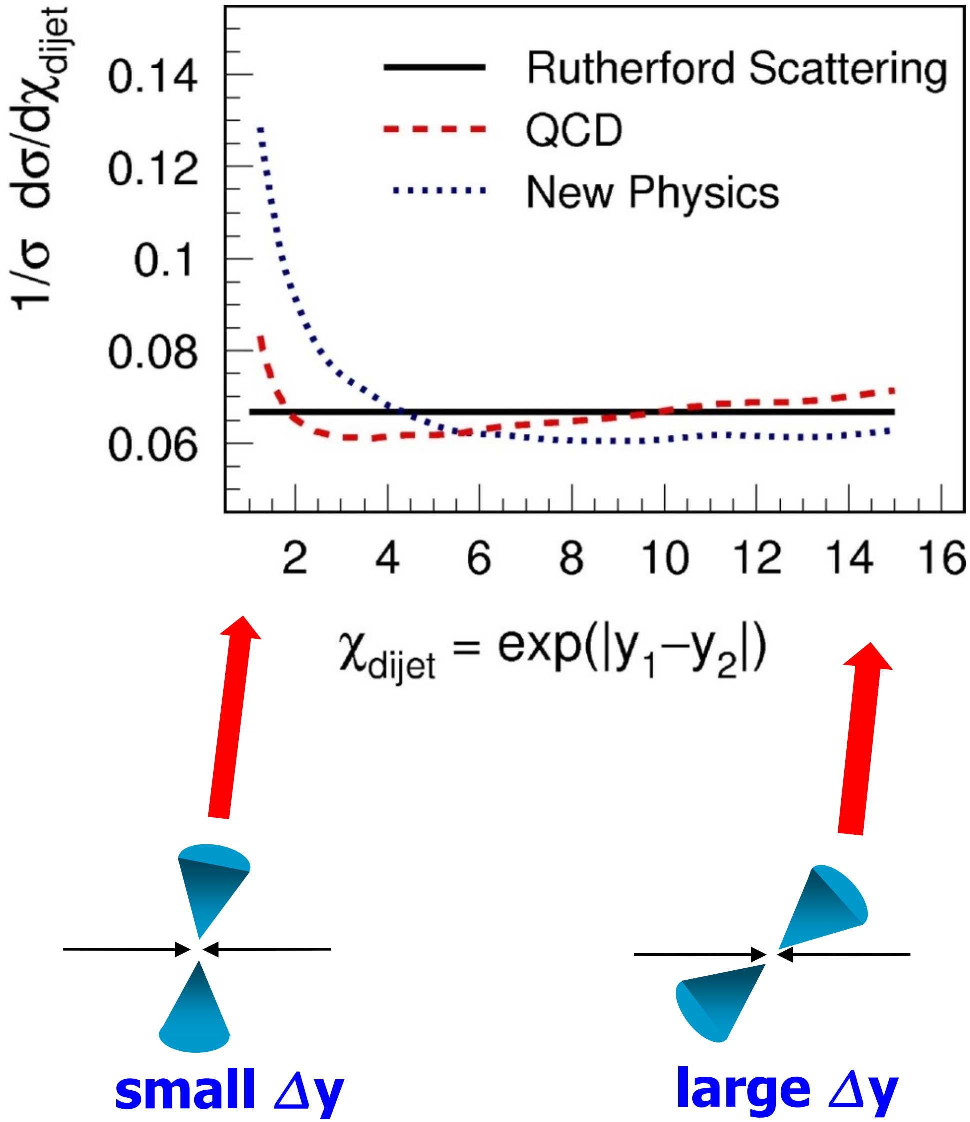
→ data with Mjj > 1.2 TeV!
→ described by NLO pQCD

- no indications for resonances

→ PDF sensitivity at large |y|-max

- CTEQ6.6 prediction too high
- MSTW2008 consistent w/ data (but correlation of experimental and PDF uncertainties!)

Dijet Angular Distribution



variable:

$$\chi_{\rm dijet} = \exp(|y_1 - y_2|)$$

at LO, related to CM scattering angle

$$\chi_{\rm dijet} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

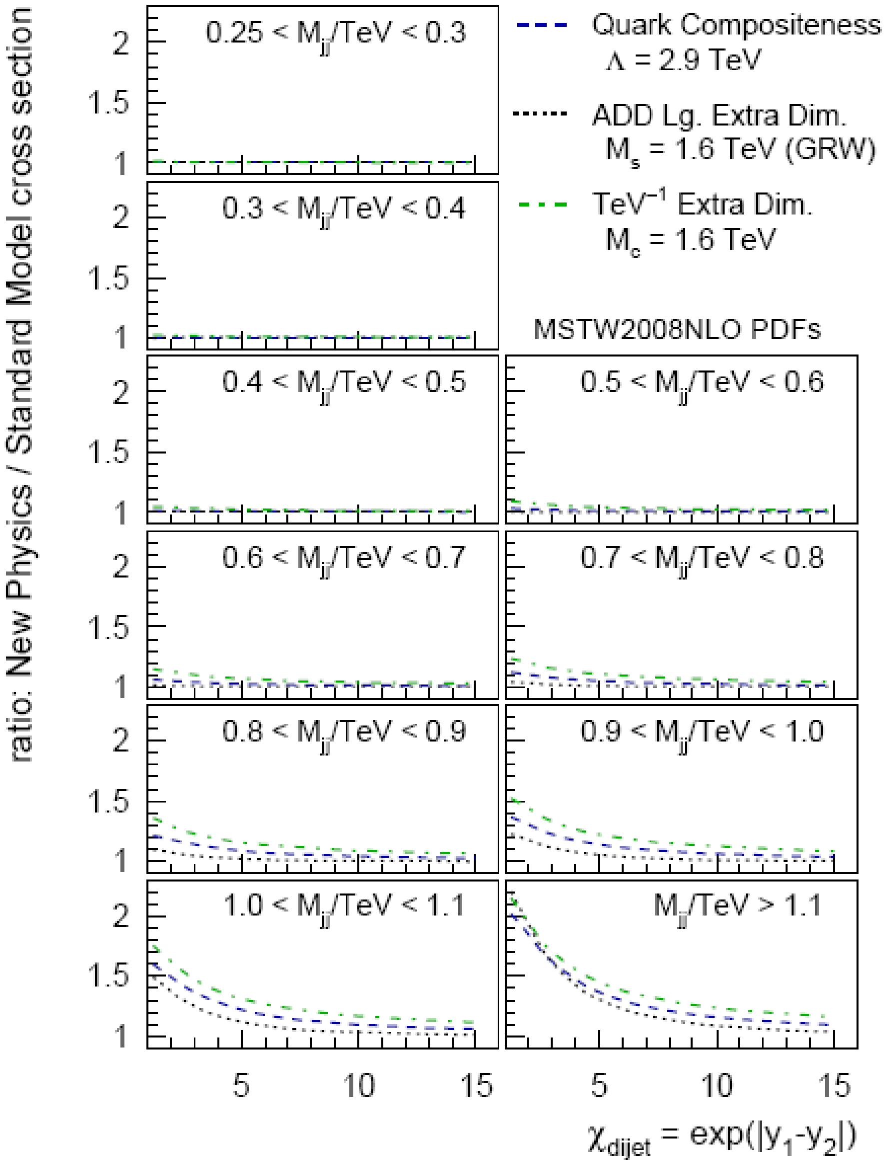
- flat for Rutherford scattering
- slightly shaped in QCD
- new physics, like
  - quark compositeness
  - extra spatial dimensions

  → enhancements at low $\chi_{\rm dijet}$

Sensitivity to New Physics

Ratio of NP/SM in different dijet mass regions

→ Highest sensitivity to New Physics at high dijet masses



"Controversy" from Run I

D0 had two Run I analyses, both searching for quark substructure:

"dijet angular distributions"	**"dijet mass distributions"**
In different **mass** regions	In different **angular** regions
→ Measure **angular** distribution	→ Measure **mass** distribution
→ Quark Compos. Limit 2.2 TeV	→ Quark Compos. Limit 2.7 TeV

Do the dijet mass distributions have a higher sensitivity?

→ No! The two analyses are essentially measuring the same quantity

→ The difference is due to poor choices in the "dijet angular distributions" analysis (see next slides)

→ In contrast, the "dijet angular distributions" are more sensitive!

Run I "dijet angular distrib."

Phys. Rev. D 64, 032003

Measure distributions in

$$\chi_{\mathrm{dijet}} \equiv \exp\left(2y^*\right)$$

in four mass regions.

Highest mass region only: M > 635 GeV

→ very high statistics >1000 events

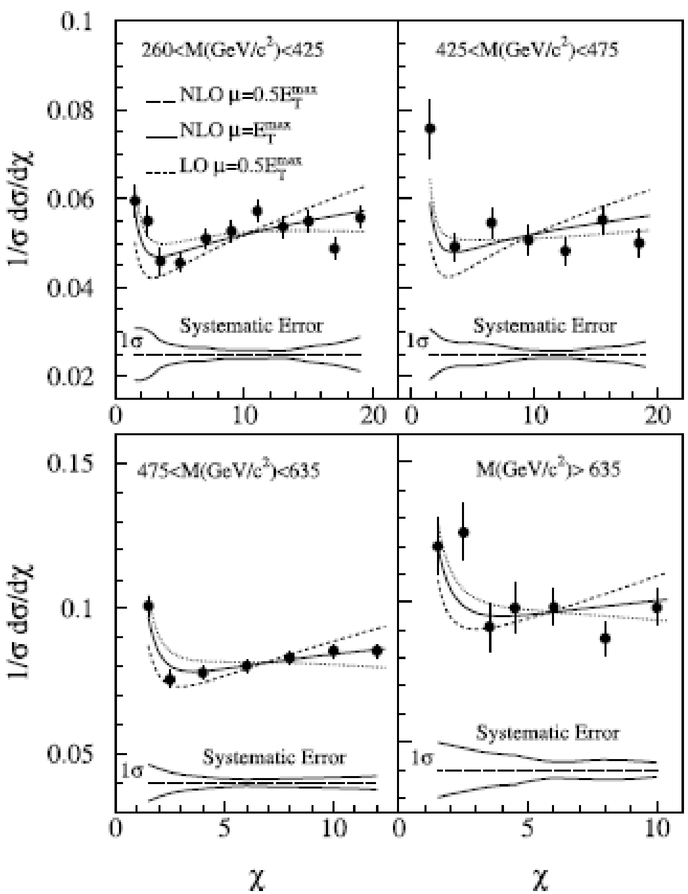


FIG. 73. Dijet angular distributions for DØ data (points) compared to JETRAD for LO (dashed line) and NLO predictions with renormalization-factorization scale $\mu=0.5E_T^{\max}$ (dotted line). The data are also compared to JETRAD NLO predictions with $\mu=E_T^{\max}$ (solid line). The errors on the data points are statistical only. The band at the bottom represents the $\pm 1\sigma$ systematic uncertainty.

Run I "dijet angular distrib."

Measure distributions in

$$\chi_{\text{dijet}} \equiv \exp(2y^*)$$

in four mass regions.

Highest mass region only: M > 635 GeV

→ very high statistics >1000 events

→ And present ratio

$$R_\chi = N(\chi < 4)/N(4 < \chi < \chi_{\text{max}})$$

= (small y* / large y*)

vs. dijet mass

Phys. Rev. D 64, 032003

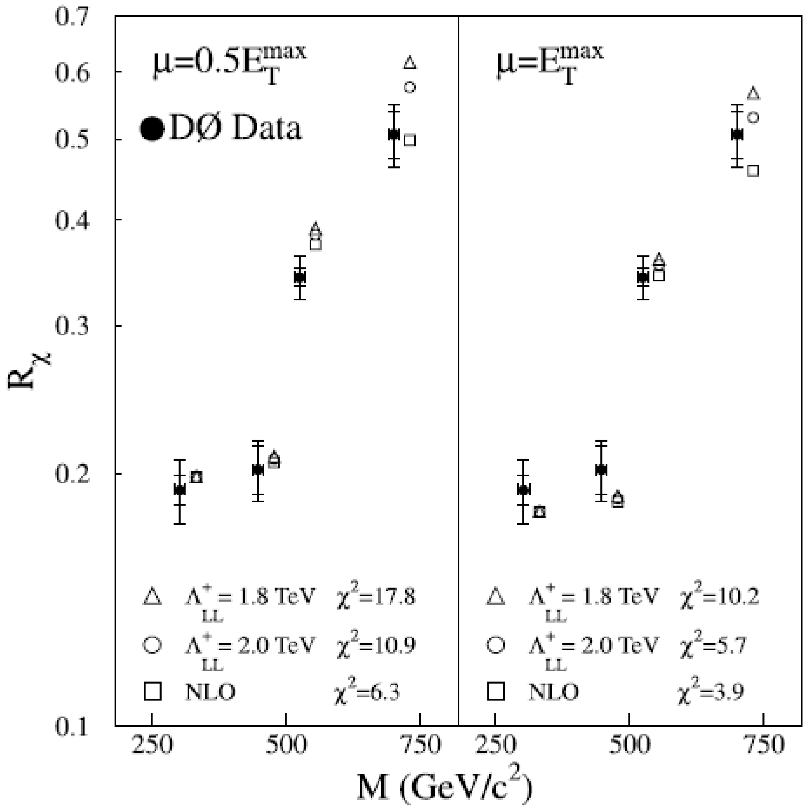


FIG. 75. R_χ as a function of dijet invariant mass for two different renormalization scales. The inner error bars are the statistical uncertainties and the outer error bars include the statistical and systematic uncertainties added in quadrature. The χ^2 values for the four degrees of freedom are shown for the different values of the compositeness scale. The data are plotted at the average mass for each mass range. The NLO points are offset in mass to allow the data points to be seen.

Run I "dijet mass"

Measure dijet mass distributions

at 0.0 < |eta| < 0.5

and at 0.5 < |eta| < 1.0

→ Present result as:
ratio (small angles / large angles)
vs. dijet mass

→ Smeared version of
(small y* / large y*)

→ Data
(although w/ low statistics)
at high masses > 800 GeV

→ Same as dijet angle, but
reach higher masses

Phys. Rev. D 64, 032003

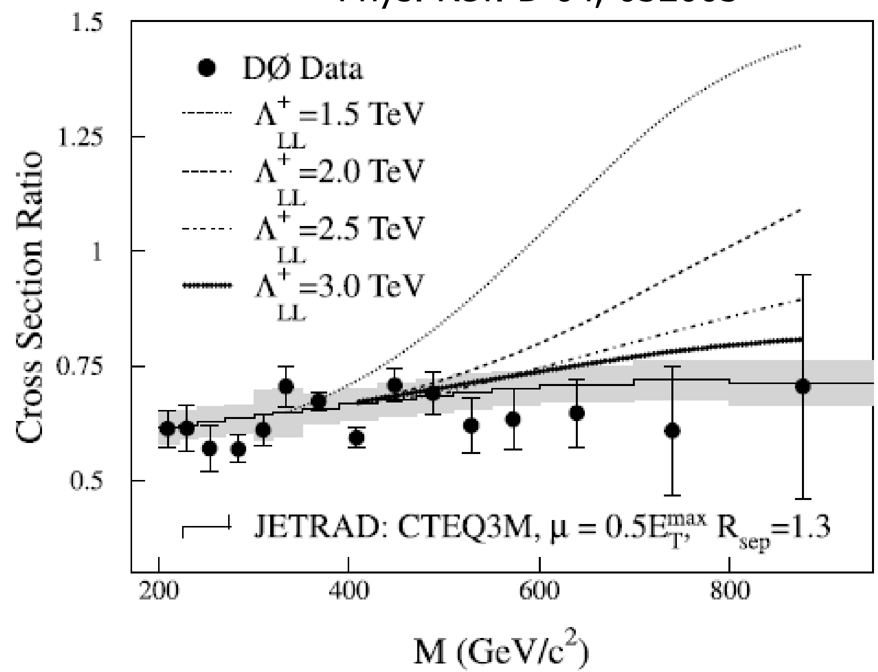


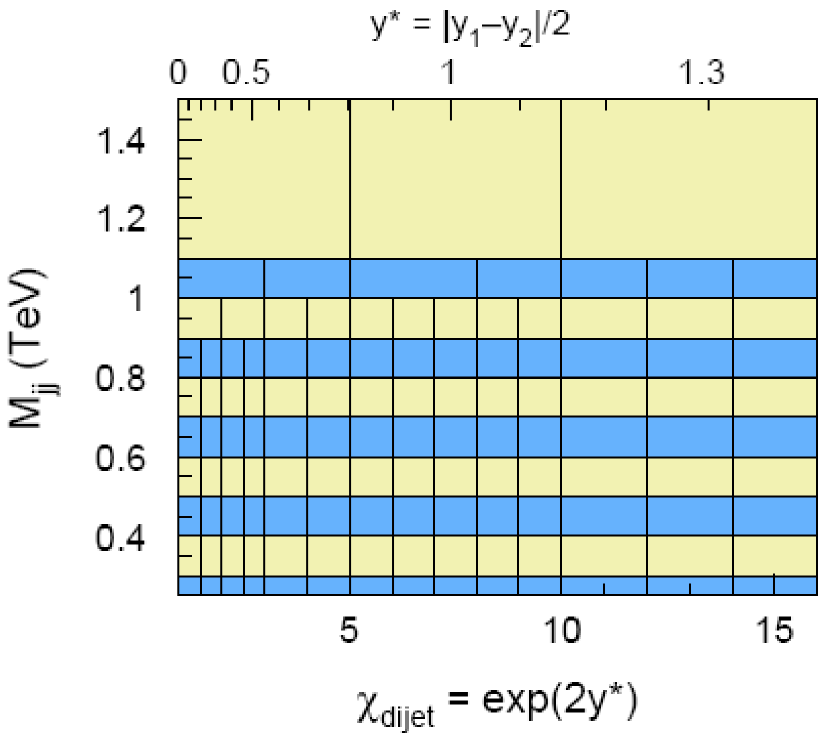
FIG. 97. The ratio of cross sections for $|\eta^{jet}|<0.5$ and $0.5<|\eta^{jet}|<1.0$ for data (solid circles) and theoretical predictions for compositeness models with various values of Λ^{+}_{LL} (various lines; see Sec. IV B for model details). The error bars show the statistical uncertainties. The shaded region represents the $\pm 1\sigma$ systematic uncertainties about the JETRAD prediction.

Dijet Angular Distribution

New analysis in **Run II**:

- Combine the best aspects of the two Run I analyses
  + further improvements:

- Measure $\chi_{\text{dijet}} \equiv \exp(2y^*)$
  (higher sensitivity in CM frame)
- Go to **highest masses**
  (even if statistics per bin is small)
- Analyze **whole shape** of distribution
- Don't reduce the distribution to 2 bins as done in $R_\chi = N(\chi < 4)/N(4 < \chi < \chi_{\text{max}})$

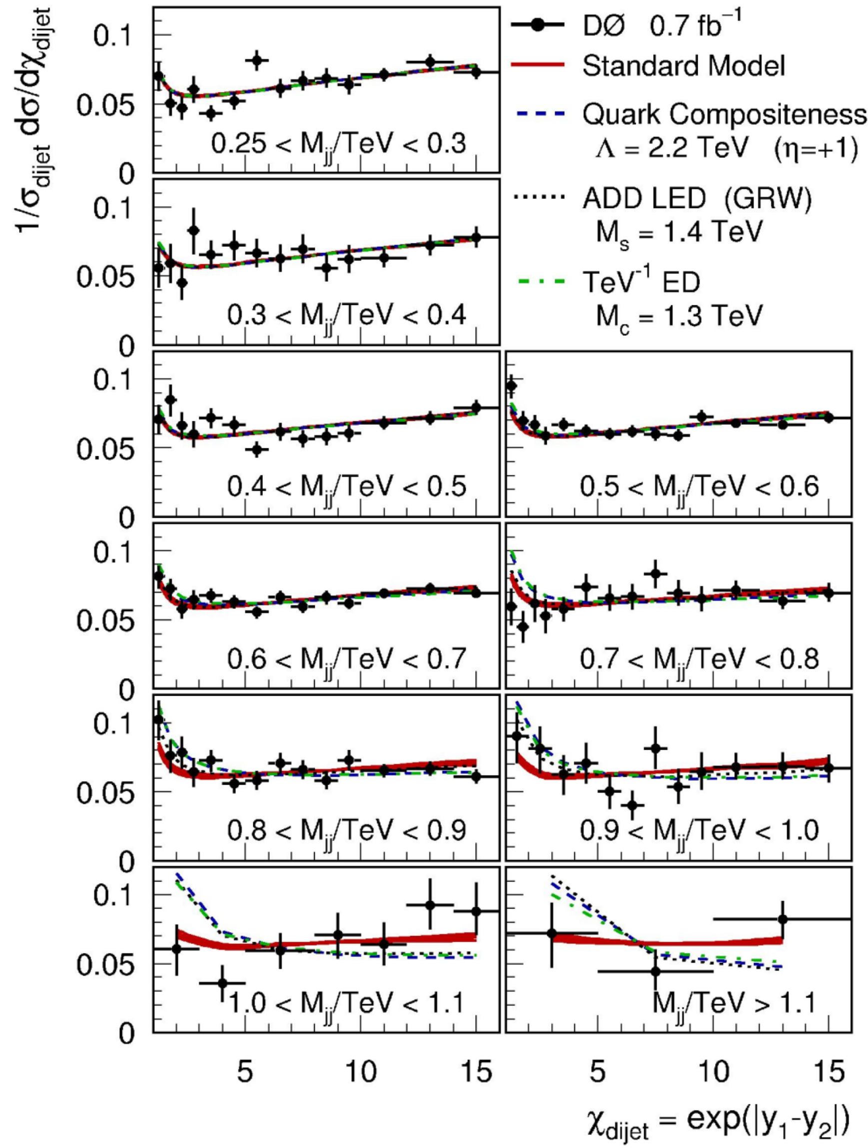


Dijet Angular Distribution

→ normalized distribution $\frac{1}{\sigma}\frac{d\sigma}{d\chi_{\mathrm{dijet}}}$

→ reduced experimental
and theoretical uncertainties

Measurement for dijet masses
from 0.25 TeV to >1.1 TeV



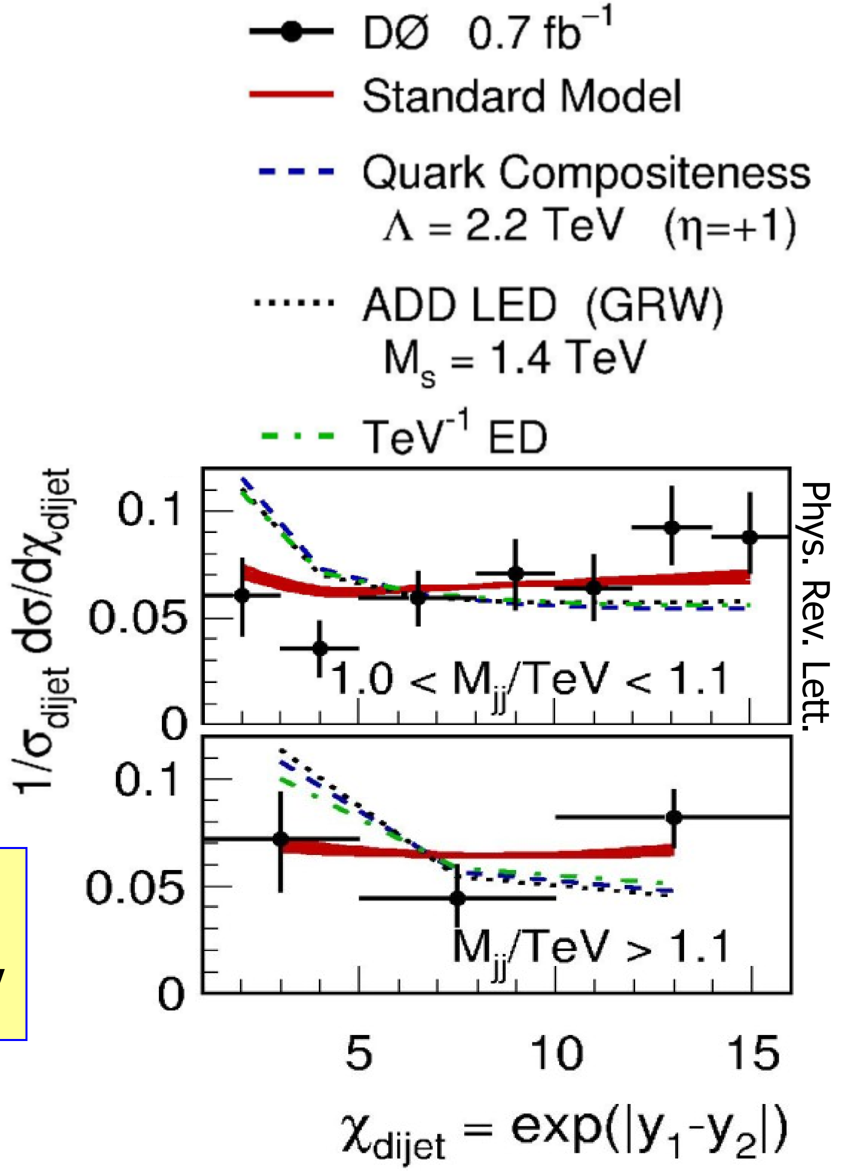
Dijet Angular Distribution

→ normalized distribution $\frac{1}{\sigma}\frac{d\sigma}{d\chi_{\mathrm{dijet}}}$

→ reduced experimental and theoretical uncertainties

Measurement for dijet masses from 0.25 TeV to >1.1 TeV

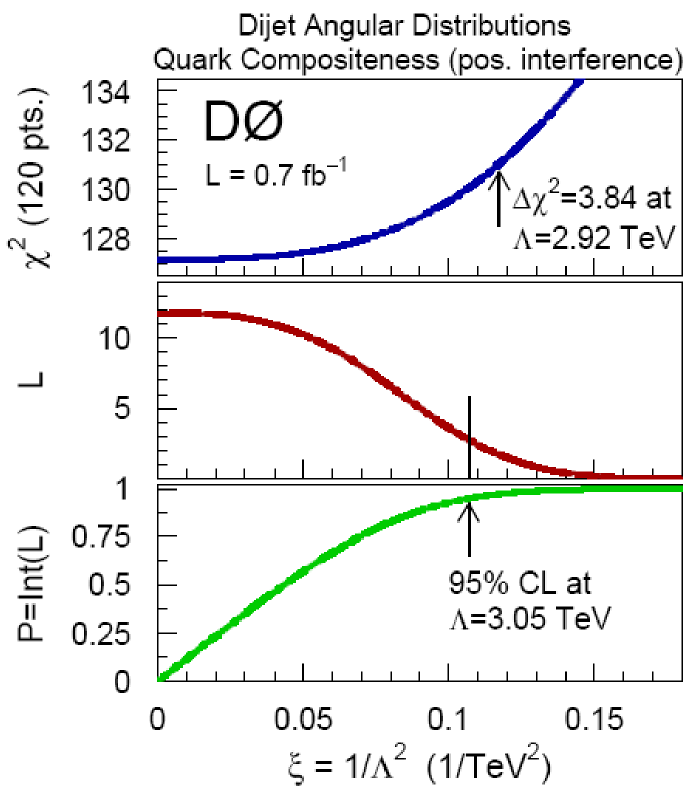
First time: Rutherford experiment above 1TeV



Dijet Angular Distribution New Physics Limits

Test multiple models at highest possible energies:

- Probing quark substructure
- Sensitive to extra spatial dimensions
  - virtual exchange of KK excitation of graviton (ADD LED)
  - virtual KK excitation of gluon (TeV-1 ED)



Use full χ_{dijet} shape of corrected data

Bayesian and $\Delta\chi^2$ methods @95%CL

- Quark Compositeness Λ > 2.9TeV
- ADD LED (GRW) Ms > 1.6 TeV
- TeV-1 ED Mc > 1.6 TeV

all: most stringent limits!

Lesson: Dijet angular distribution

Dijets double differentially vs. (chi, Mjj)

- No real difference between D0 Run I measurements of dijet mass ratio (central / forward) and dijet angular distribution
  → both are essentially the same
  → different sensitivity due to different choices of mass bins
- Most information & highest sensitivity by measuring dijet **angular distribution** (y*) and analyzing the **full shape**
- Optimize sensitivity:
  - Don't stop at low masses (don't insist on high statistics/chi bin)
  - Better: extend to higher masses → even with less statistics/bin
    → higher sensitivity

recent preliminary CDF result "limited by systematics"
→ indication of wrong method

→ if one is not yet limited by statistics, one should measure at higher masses (statistics limited but higher sensitivty)

Dijets beyond 2 → 2

Dijet azimuthal decorrelation

→ Monte Carlo tuning

Multijet ratio: R3/2

higher order processes

Strategy:

Testing higher order processes,
while insensitive to non-perturbative physics:

- Hadronization
- Underlying event
- PDFs

→ Only to strong dynamics

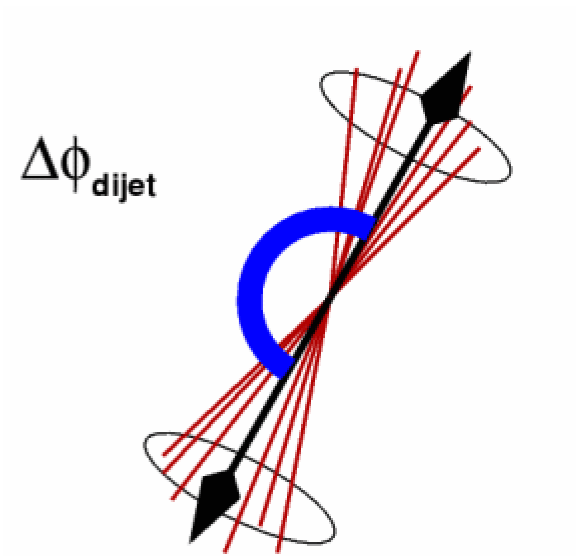
→ Use **normalized** distributions (i.e. ratios of cross sections) sensitive to 3-jet production

- Dijet azimuthal decorrelations
- Multijet ratios → R3/2

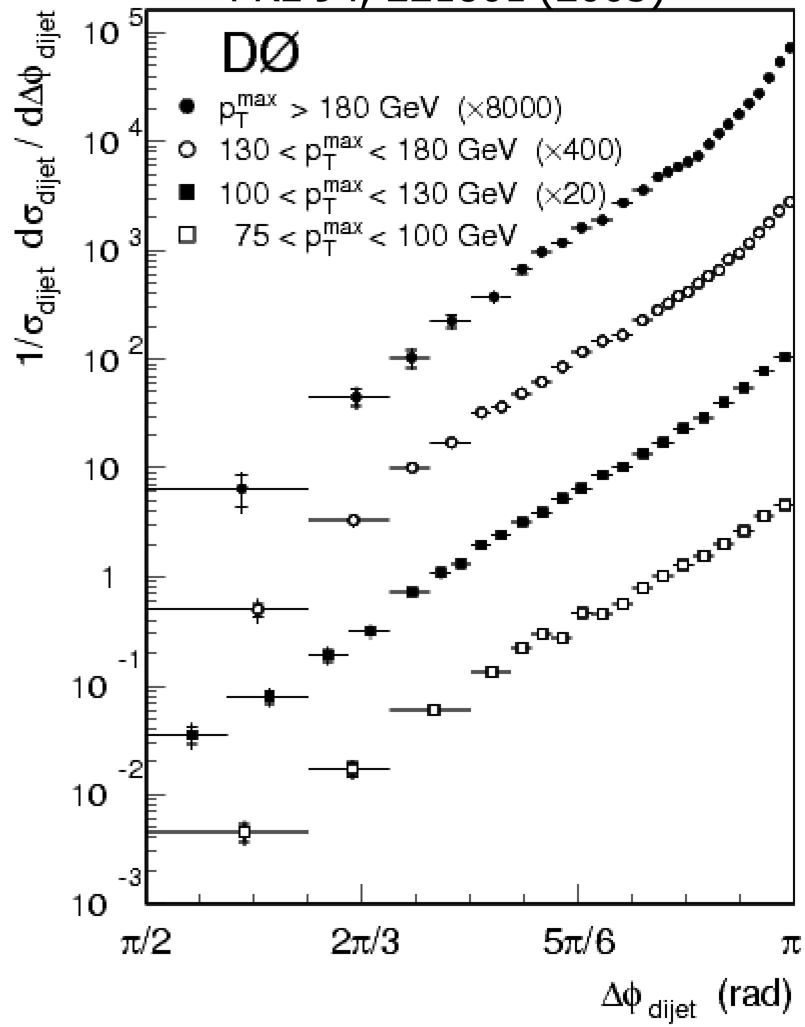
Dijet Azimuthal Decorrelation

Idea: Dijet Azimuthal Angle is Sensitive to Soft & Hard Emissions:

- Test Parton-Shower
- Test 3-Jet NLO



PRL 94, 221801 (2005)



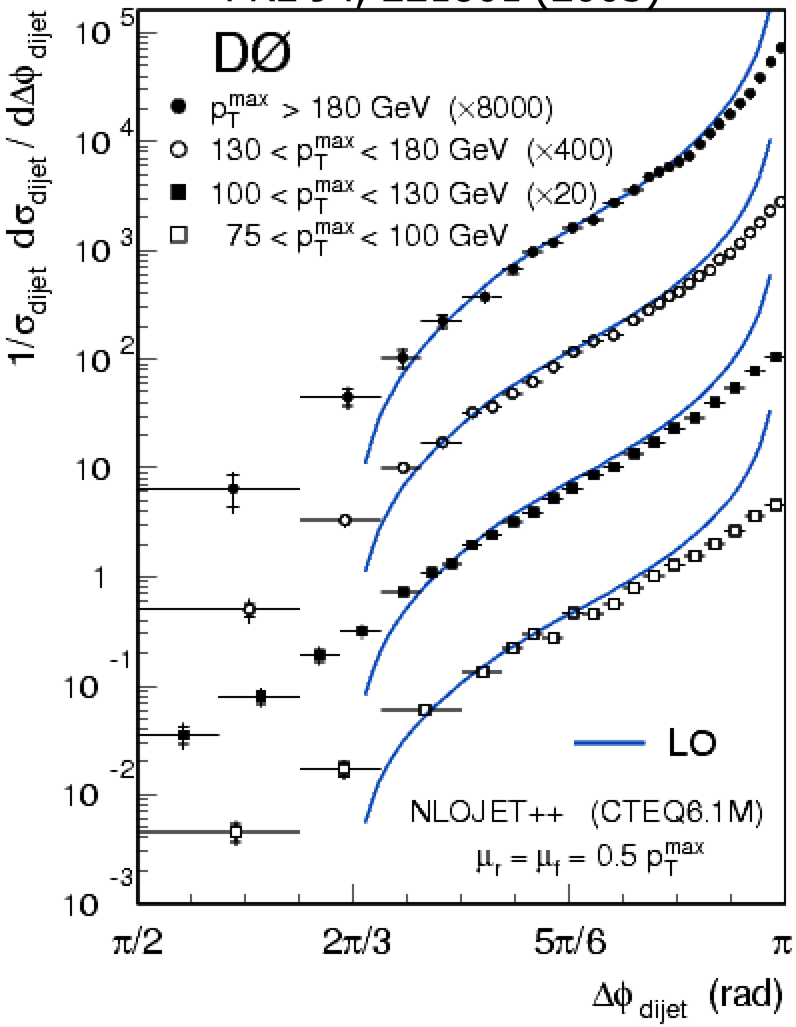
Dijet Azimuthal Decorrelation

PRL 94, 221801 (2005)

Compare with theory:

- LO has Limitation >2pi/3

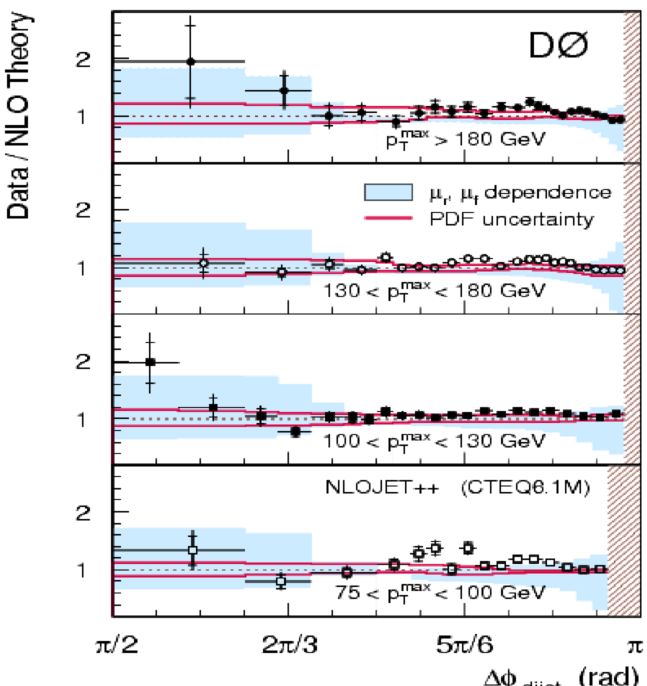
  & Divergence towards pi



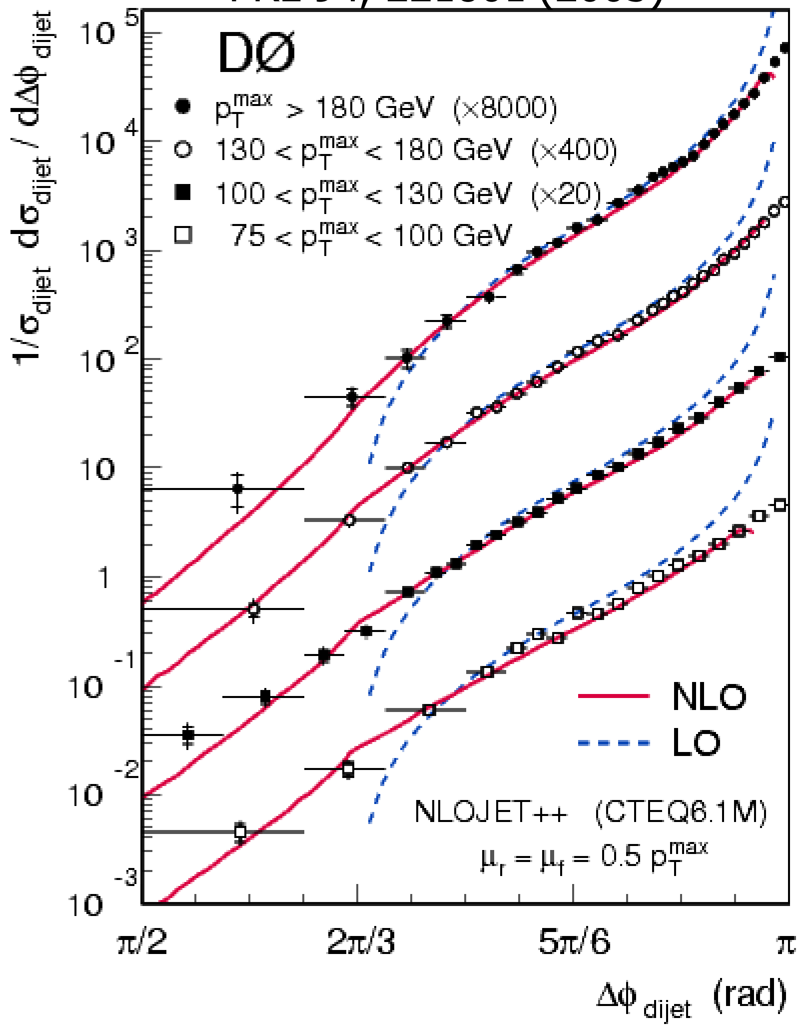
Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3
  & Divergence towards pi
- NLO is very good – down to pi/2
  & better towards pi
  … still: resummation needed



PRL 94, 221801 (2005)



Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3
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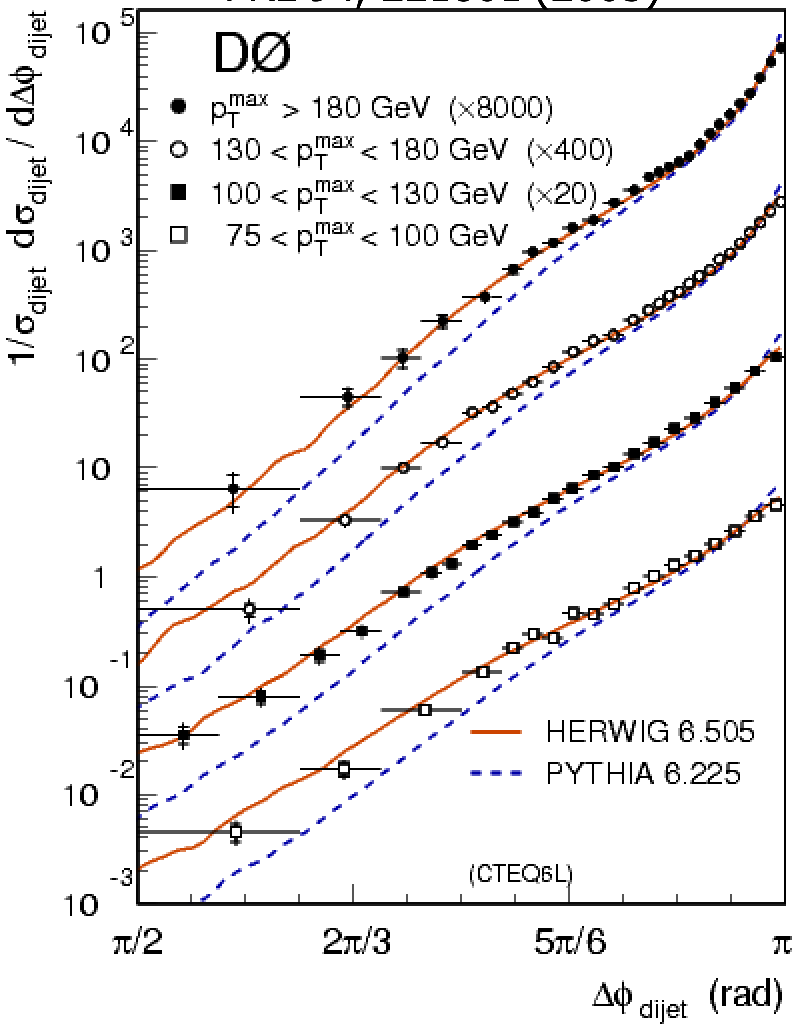
- HERWIG is perfect “out-the-box”
- PYTHIA is too low in tail …

PRL 94, 221801 (2005)



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- PYTHIA is too low in tail …
  … but it can be tuned (tune DW)
  ("tune A" is too high!)

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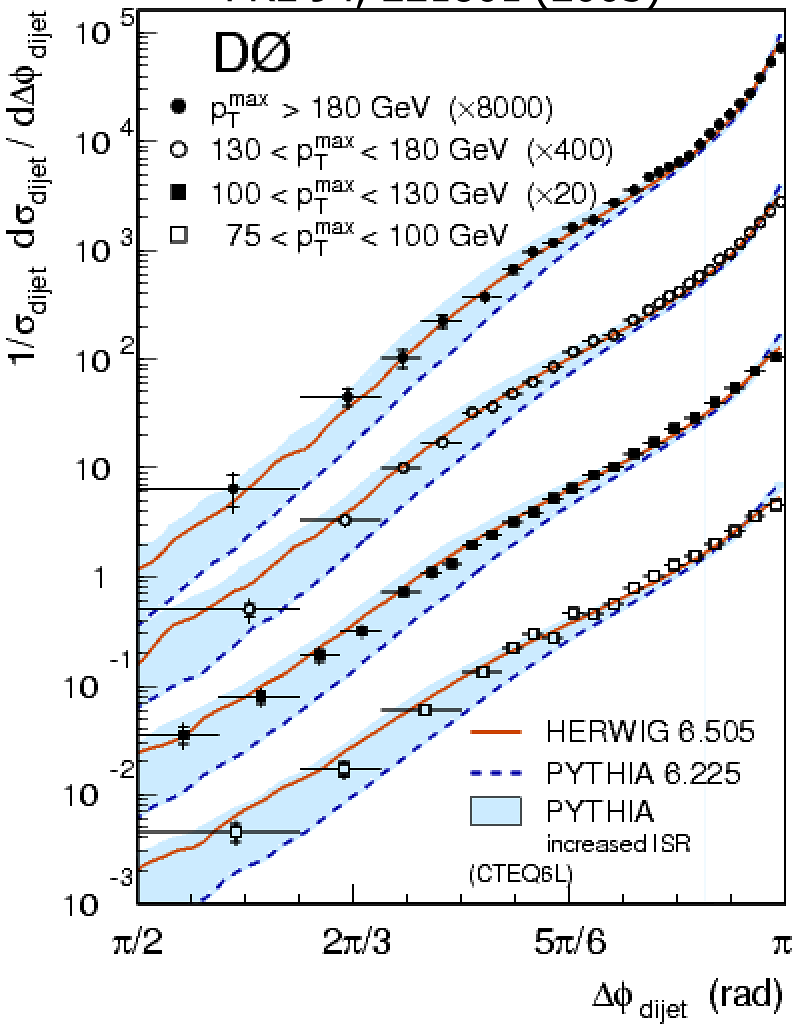

Dijet Azimuthal Decorrelation

Compare with theory:

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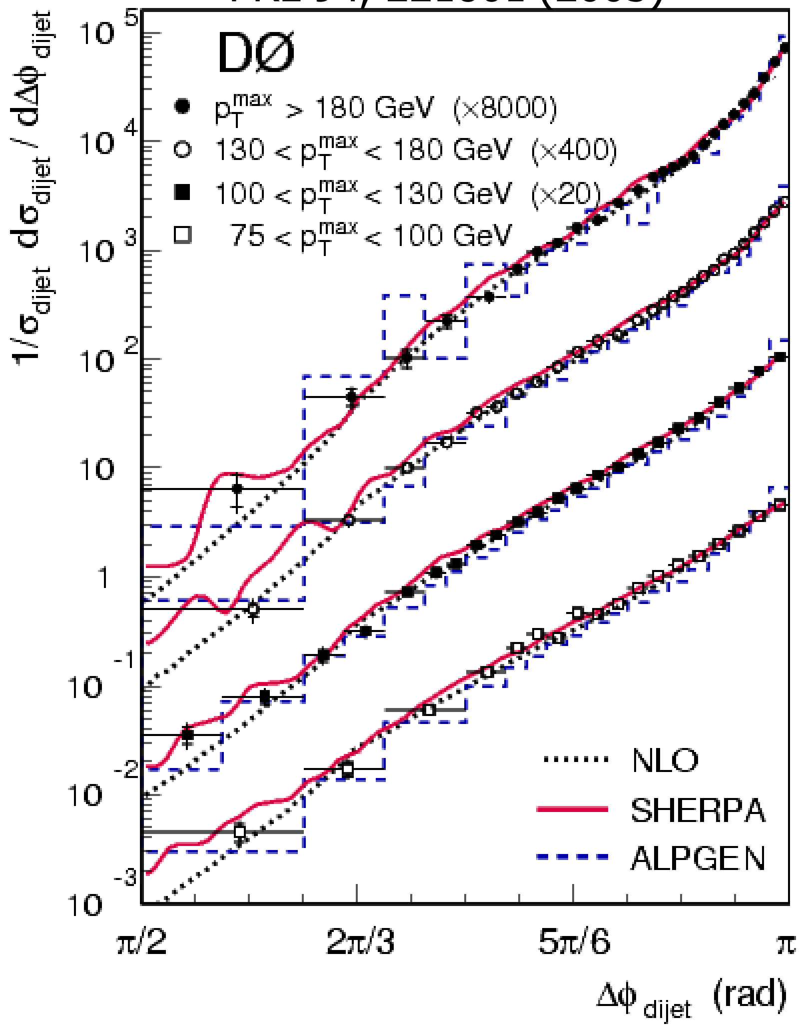
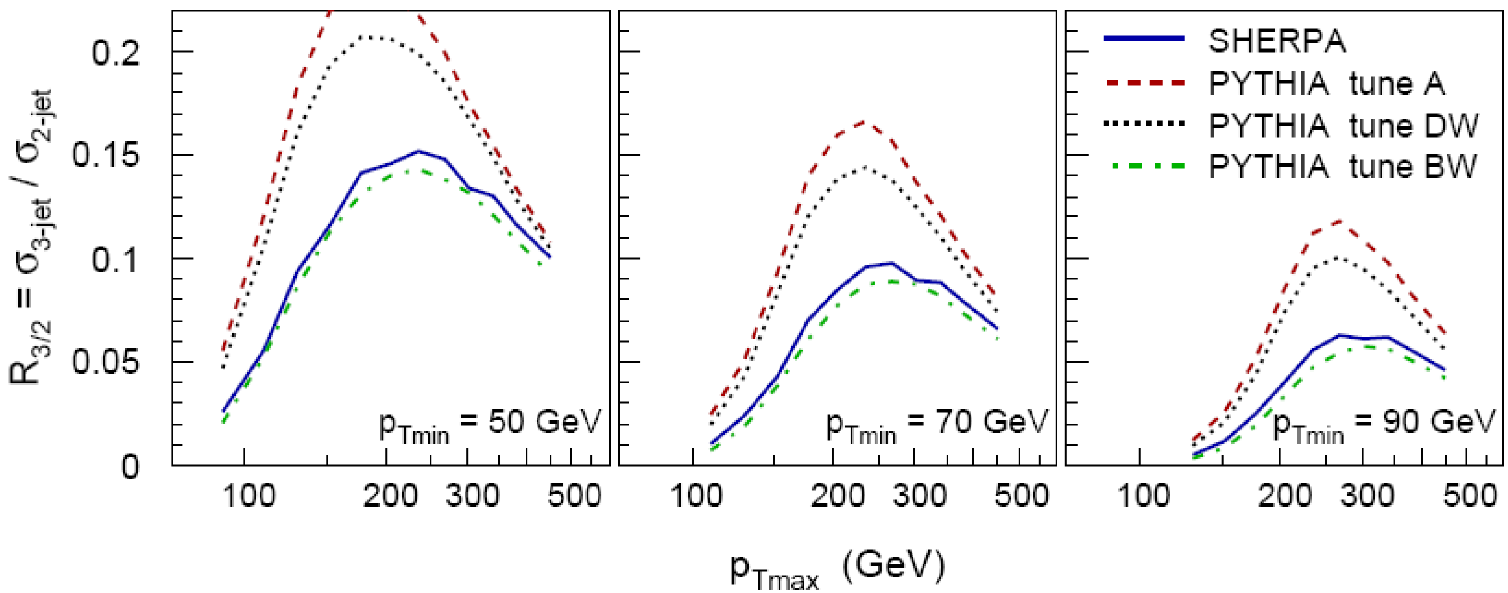
- HERWIG is perfect "out-the-box"
- PYTHIA is too low in tail …
  … but it can be tuned (tune DW)
  ("tune A" is too high!)
- SHERPA is great
- ALPGEN looks good – but low efficiency → large stat. fluctuations

PRL 94, 221801 (2005)



Multijet ratio R3/2

Study ratio of 3-jet and 2-jet cross sections (for jets above p_{Tmin}) as a function of leading jet p_T (p_{Tmax})



For DeltaPhi → agreement between data, PYTHIA tune DW, SHERPA

Here: strong disagreement between PYTHIA tune DW and SHERPA

… where is the data?? → coming soon …

Lesson from DeltaPhi & R3/2

Most observables used in tuning are sensitive to soft physics only

→ Danger: optimization of hard physics in parton shower to soft observables may screw up description of hard processes

Important: Measurements of observables, sensitive to hard physics

→ DeltaPhi, R3/2 are unique sources of information for MC tuning

Conclusions

… see lessons from

Inclusive jets

Dijets

"beyond 2→2"

Lessons from incl. jets (1)

The inclusive jet cross section – double differentially vs. (p_T ,y)

- Consistency between CDF and D0 (and between cone/k_T)
- Traditionally THE measurement to constrain PDFs
  → although triple dijet cross section (p_T,y*,yboost) is more sensitive
- More useful if measured with IR safe jet algorithms
  → if possible successive recombination: k_T, CA, anti-k_T
- this measurement requires
  - best possible energy calibration
    → Calibrate jets / or detector objects?
  - Knowledge of correlations of uncertainties (calibration, resolution) over p_T and rapidity: D0 uses 48 separate sources

Lessons from incl. jets (2)

The inclusive jet cross section – double differentially vs. (p_T,y)

- Important testing ground: Measurement of
  - radius dependence (for given algorithm)
  - Jet algorithm dependence (for given radius)

  → both require correlations of uncertainties between jets for different radii / different algorithms
  → not available for existing CDF / ZEUS measurements
  → easier if energy calibration is done for energy depositions (cells/clusters/towers) not possible if energy calibration
  → correlations must be documented in publications

- Limited sensitivity to alpha-s:
  → no independent test of RGE, since alpha-s extraction requires input from PDFs, which already use alpha-s and the RGE in the evolution.
  → determination restricted to region where RGE was found to be valid

Lesson: Dijet angular distribution

Dijets double differentially vs. (chi, Mjj)

- No real difference between D0 Run I measurements of dijet mass ratio (central / forward) and dijet angular distribution
  → both are essentially the same
  → different sensitivity due to different choices of mass bins
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Lesson from DeltaPhi & R3/2

Most observables used in tuning are sensitive to soft physics only

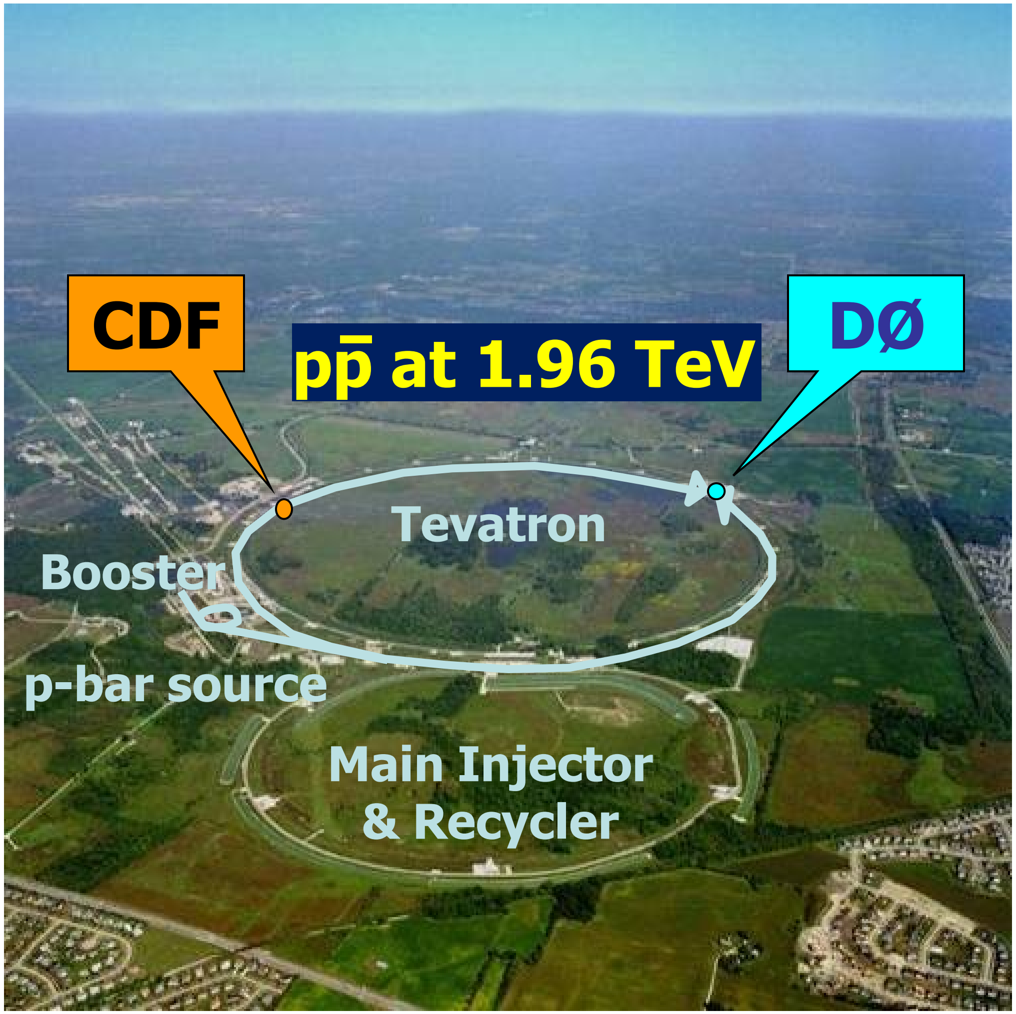
→ Danger: optimization of hard physics in parton shower to soft observables may screw up description of hard processes

Important: Measurements of observables, sensitive to hard physics

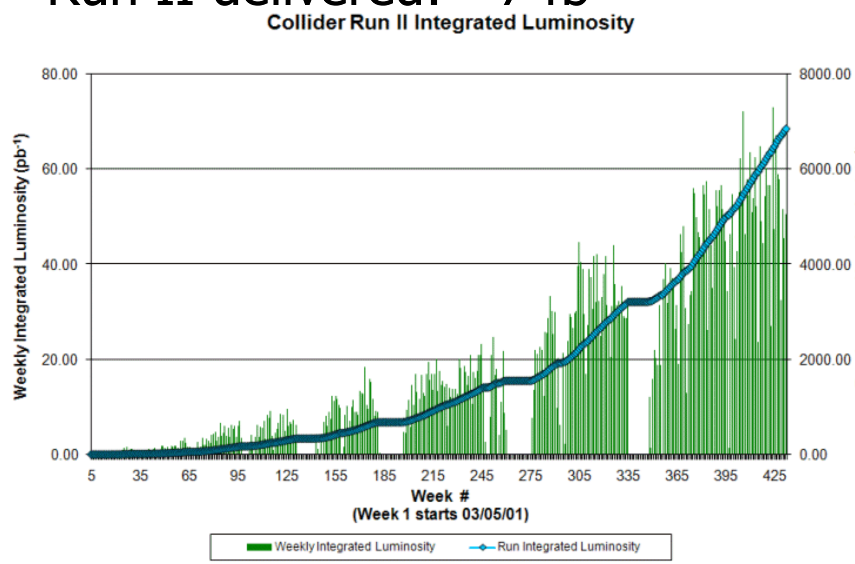
→ DeltaPhi, R3/2 are unique sources of information for MC tuning

backup

Fermilab Tevatron - Run II



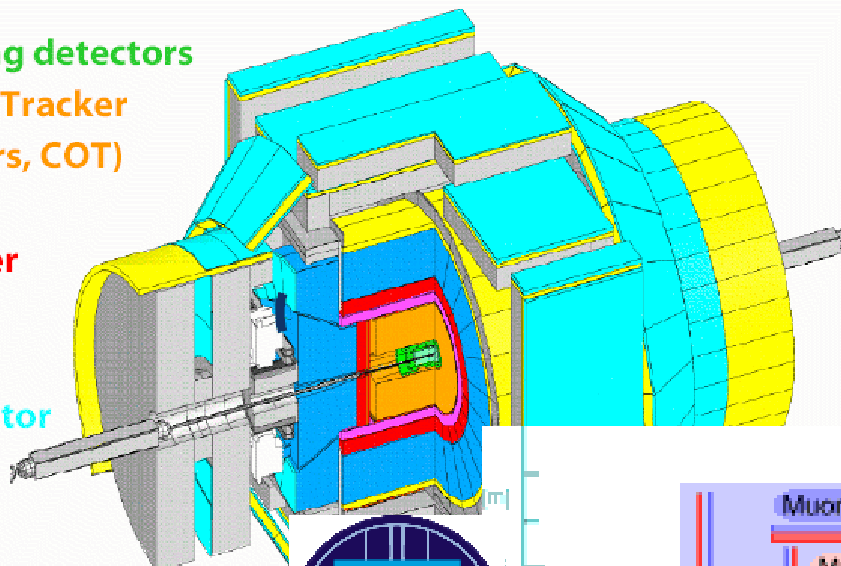
- 36x36 bunches
- bunch crossing 396 ns
- Run II started in March 2001
- Peak Luminosity:3.5E32 cm^{-2} sec^{-1}
- Run II delivered: ~7 fb^{-1}



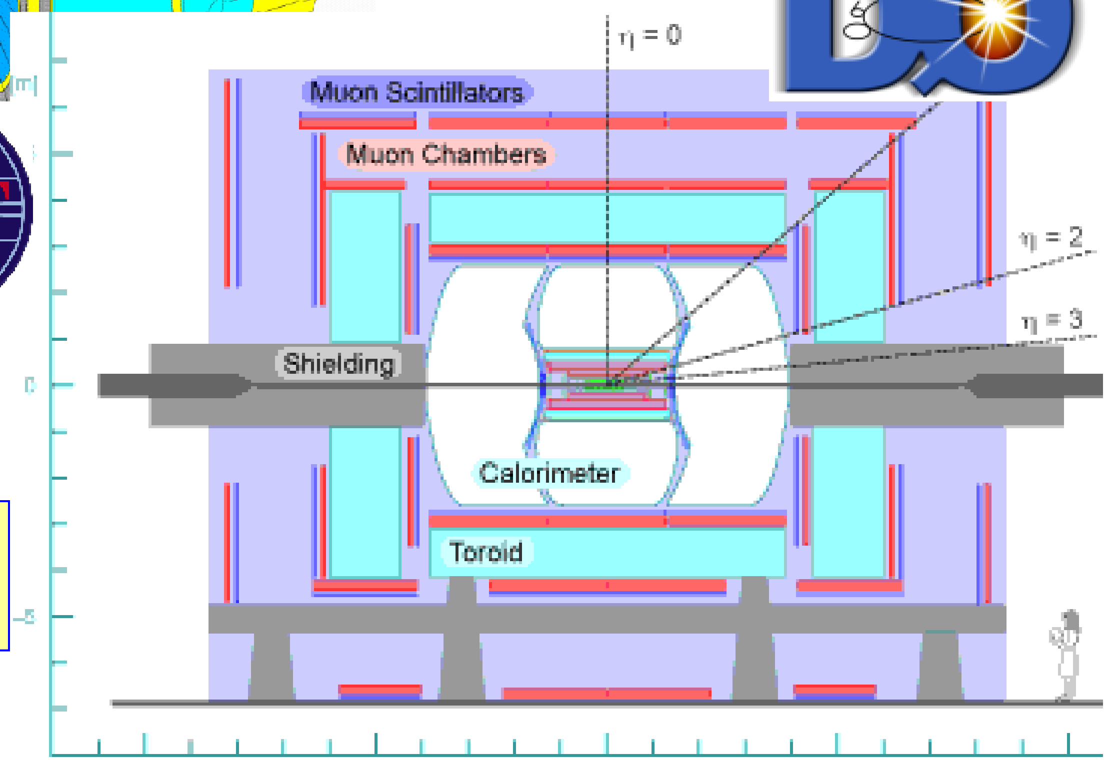
- Run II Goal: 12 fb^{-1} end of 2011

Run II Detectors

- Silicon tracking detectors
- Central Outer Tracker (drift chambers, COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding



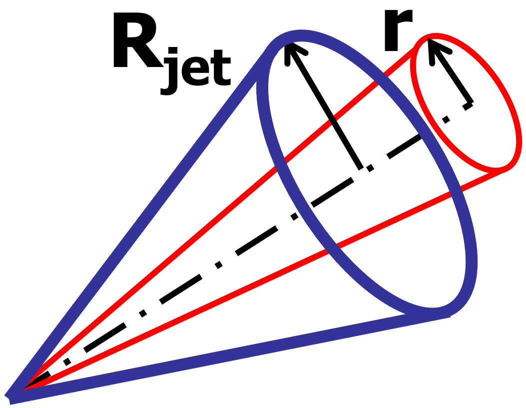
Multi-Purpose Detectors:
- Tracking
- Calorimeter
- Muon System



New in D0 for Run IIb:
Innermost “Layer 0” Silicon

Internal Jet Structure

CDF, PRD, hep-ex/0505013 (170pb-1)

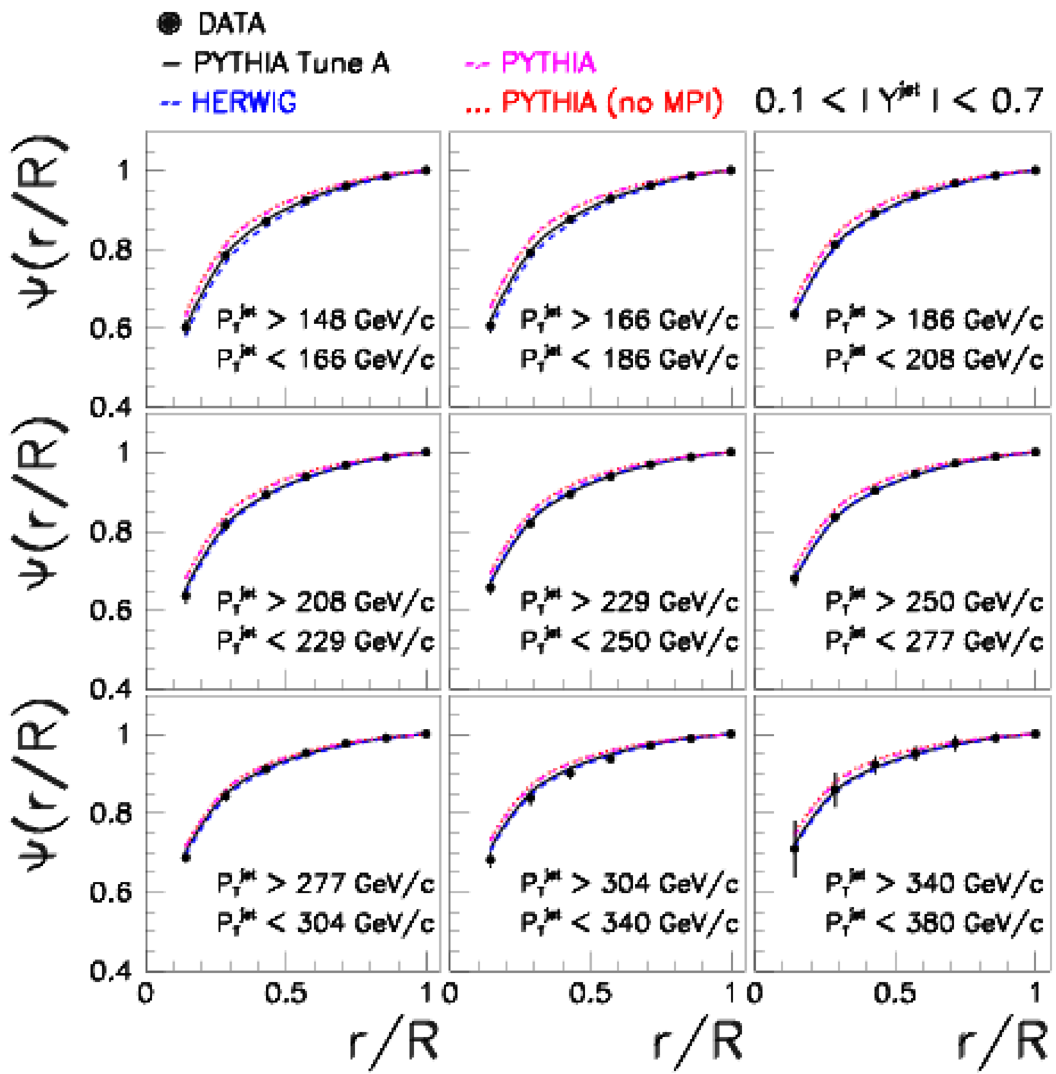


Integrated Jet Shape:

Fractional pT in Subcone vs.(r/R)

Sensitive to Soft and Hard Radiation – and UE

Well-Described by (tuned) MCs



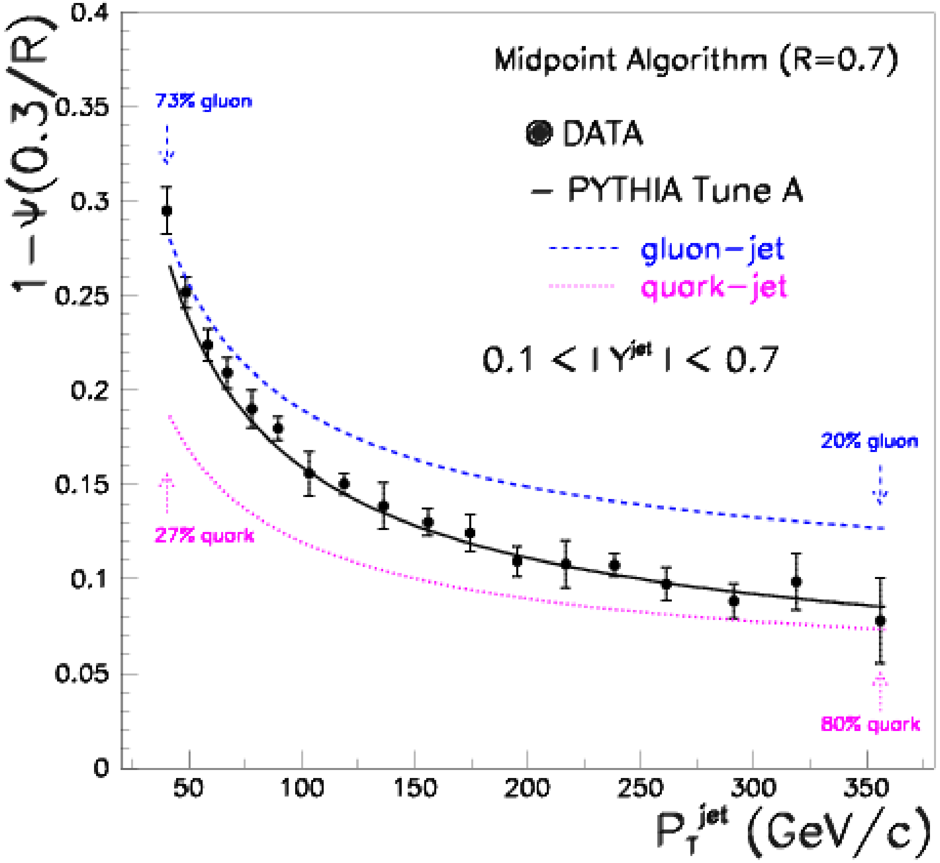
Internal Jet Structure

At fixed r=0.3 (38<pT<400GeV)

study pT dependence of predicted Psi(r/R) for quark- & gluon-jets

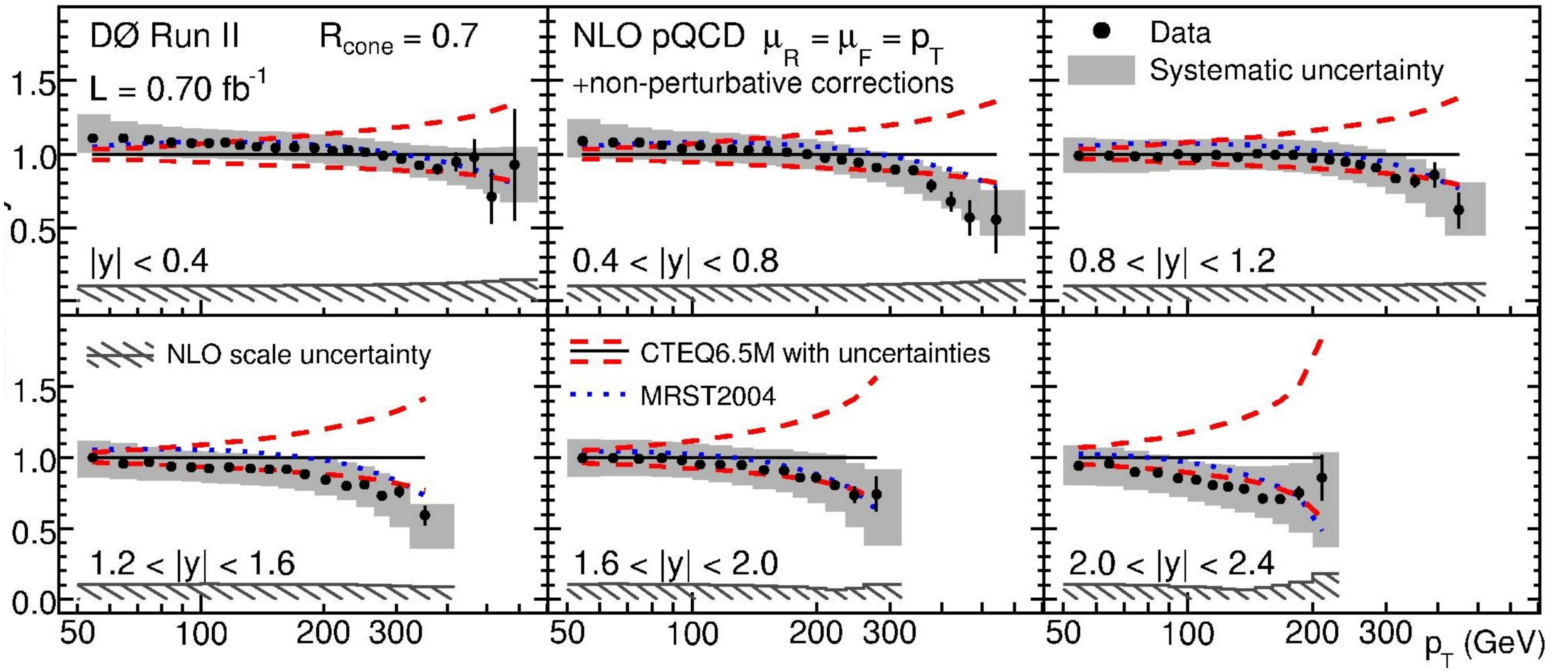
→ significant difference

quark- & gluon-jet mixture in tuned PYTHIA gives good description of data



Inclusive Jet Cross Section

submitted to PRL arXiv:/0802.2400 [hep-ex]



- data are well-described by NLO pQCD
- experimental uncertainties: smaller than PDF uncertainties!!
- data favor lower edge of CTEQ 6.5 PDF uncertainties at high p_T
- shape well described by MRST2004

→ data are used in MSTW2008 PDFs (LO, NLO, NNLO)

Run I: dijet angular distributions

TABLE XXXV. Dijet angular cross section $(100/N)(dN/d\chi) \pm$ statistical $\pm$ systematic uncertainties for the four mass bins (GeV/c^2).

χ	$260<M<425$			$425<M<475$			$475<M<635$			$M>635$		
	value±	stat.±	syst.	value±	stat.±	syst.	value±	stat.±	syst.	value±	stat.±	syst.
1.5	5.95 ±	0.35 ±	0.58	7.58 ±	0.66 ±	2.08	10.08 ±	0.33 ±	0.63	11.98 ±	0.99 ±	0.49
2.5	5.50 ±	0.33 ±	0.54	4.26 ±	0.50 ±	0.75	7.56 ±	0.28 ±	0.36	12.49 ±	1.01 ±	0.78
3.5	4.59 ±	0.30 ±	0.31	4.96 ±	0.53 ±	0.67	7.83 ±	0.29 ±	0.33	9.11 ±	0.86 ±	0.61
4.5	4.57 ±	0.30 ±	0.28	5.54 ±	0.56 ±	1.04	7.71 ±	0.28 ±	0.25	9.79 ±	0.89 ±	0.23
5.5	4.56 ±	0.30 ±	0.25	5.29 ±	0.55 ±	0.86	7.87 ±	0.29 ±	0.17	10.06 ±	0.91 ±	0.26
6.5	5.10 ±	0.32 ±	0.23	6.26 ±	0.60 ±	0.73	8.17 ±	0.29 ±	0.16	9.58 ±	0.88 ±	0.51
7.5	5.10 ±	0.32 ±	0.19	4.83 ±	0.53 ±	0.33	8.70 ±	0.30 ±	0.20	9.30 ±	0.87 ±	0.57
8.5	5.61 ±	0.34 ±	0.15	4.40 ±	0.50 ±	0.16	7.91 ±	0.29 ±	0.21	8.08 ±	0.81 ±	0.42
9.5	4.93 ±	0.32 ±	0.09	5.60 ±	0.57 ±	0.25	8.46 ±	0.30 ±	0.24	8.96 ±	0.85 ±	0.30
10.5	6.04 ±	0.35 ±	0.06	5.22 ±	0.55 ±	0.37	8.62 ±	0.30 ±	0.27	10.65 ±	0.93 ±	0.41
11.5	5.40 ±	0.33 ±	0.04	4.30 ±	0.50 ±	0.40	8.38 ±	0.30 ±	0.29			
12.5	5.33 ±	0.33 ±	0.08	4.75 ±	0.52 ±	0.52	8.69 ±	0.30 ±	0.36			
13.5	5.41 ±	0.33 ±	0.14	5.43 ±	0.56 ±	0.65						
14.5	5.40 ±	0.33 ±	0.20	5.69 ±	0.57 ±	0.70						
15.5	5.60 ±	0.34 ±	0.28	6.18 ±	0.60 ±	0.76						
16.5	4.81 ±	0.31 ±	0.30	4.70 ±	0.52 ±	0.57						
17.5	4.95 ±	0.32 ±	0.38	4.83 ±	0.53 ±	0.56						
18.5	5.78 ±	0.34 ±	0.53	5.01 ±	0.54 ±	0.55						
19.5	5.37 ±	0.33 ±	0.57	5.17 ±	0.55 ±	0.55						

- Mass range >635 GeV:
  10 bins with statistical errors <10% → more than 1000 events
- Would have allowed to have a significantly higher mass range

Photons

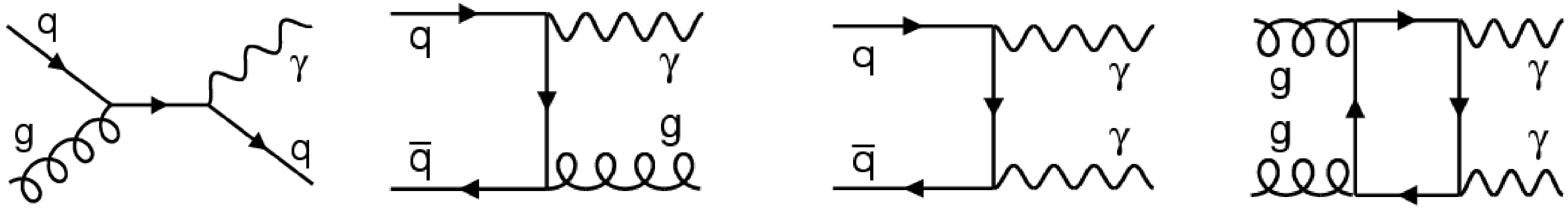
test theory

fixed order: NLO

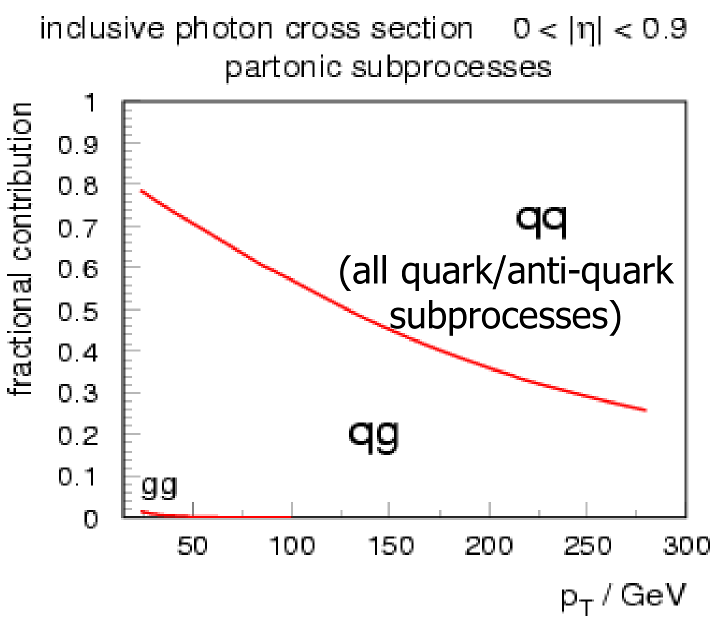
resummation

PDFs

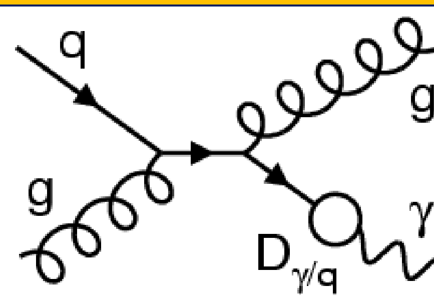
Direct Photon Production



direct photons emerge unaltered from the hard subprocess
→ direct probe of the hard scattering dynamics
→ sensitivity to PDFs (gluon!) …but only if theory works

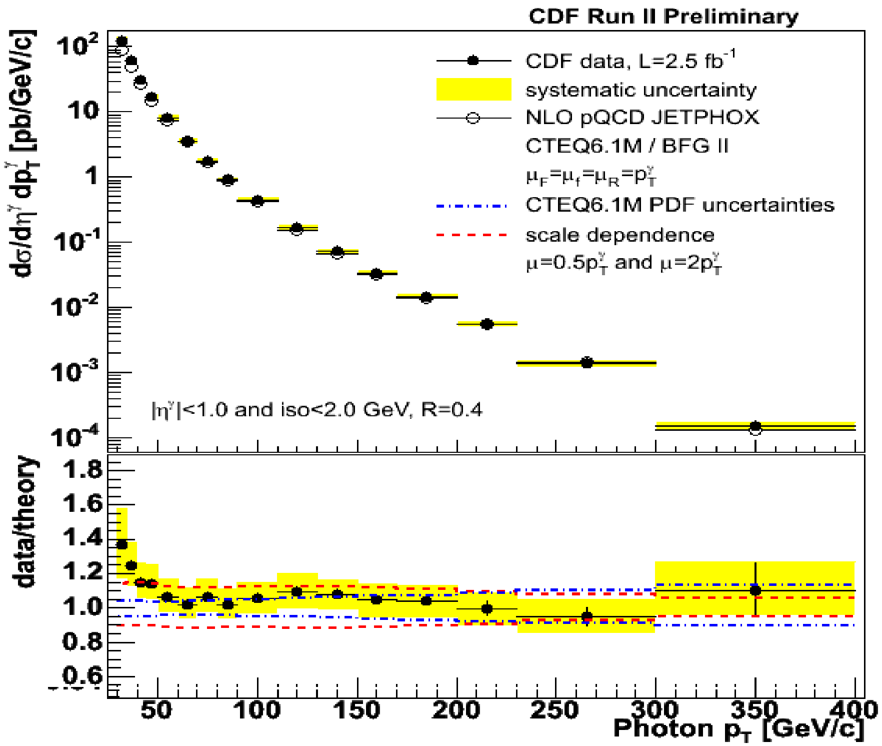


also fragmentation contributions:

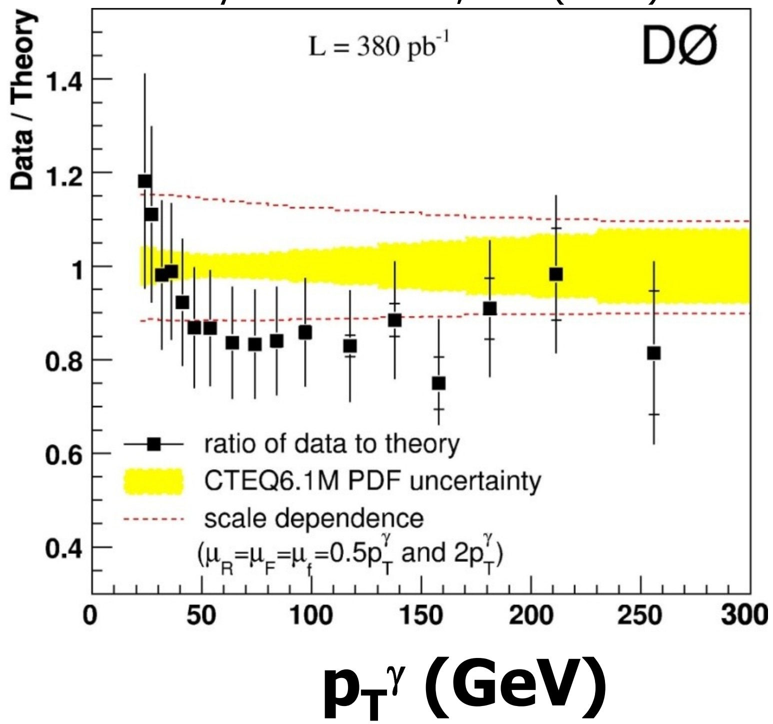


suppress by isolation criterion
→ observable: **isolated** photons

Incl. Isolated Photons



Phys. Lett. B 639, 151 (2006)



- CDF and D0 measurements: 20< p_T <400GeV → agreement
- data/theory: difference in low p_T shape
- experimental and theory uncertainties > PDF uncertainty
  → no PDF sensitivity yet
- first: need to understand discrepancies in shape

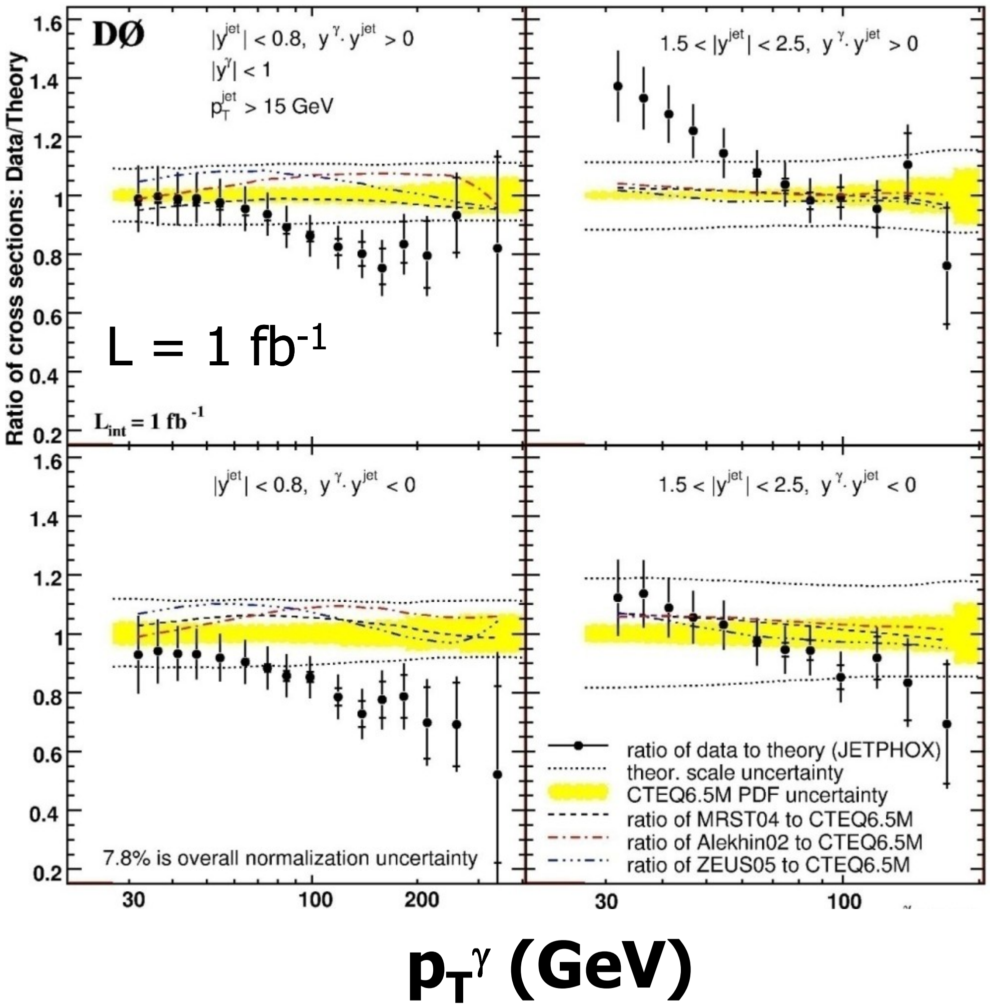
Isolated Photon + Jet

investigate source for disagreement
→measure more differential:

- tag **photon and jet**
  → reconstruct full event kinematics

- measure in 4 regions of y^{γ} / $y^{\mathbf{jet}}$
  - photon: central
  - jet: central / forward
  - same side / opposite side

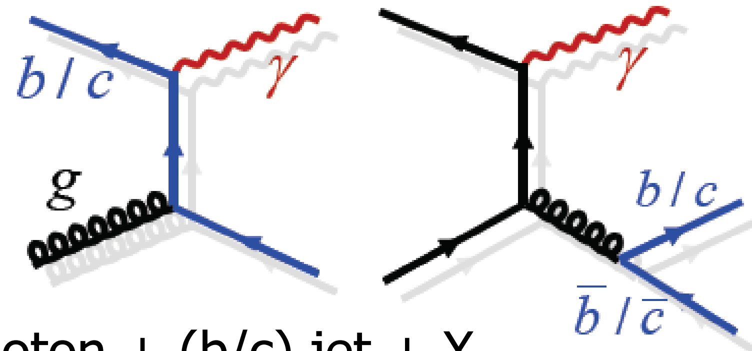
Phys. Lett. B 666, 2435 (2008)



discrepancies in data/theory
→ figure out what is missing…

- higher orders?
- resummation?
- …???

Isolated Photon + HF Jet



Photon + (b/c) jet + X

Photon p_T : 30-150 GeV

0.01<x<0.3 → b, c, gluon PDF

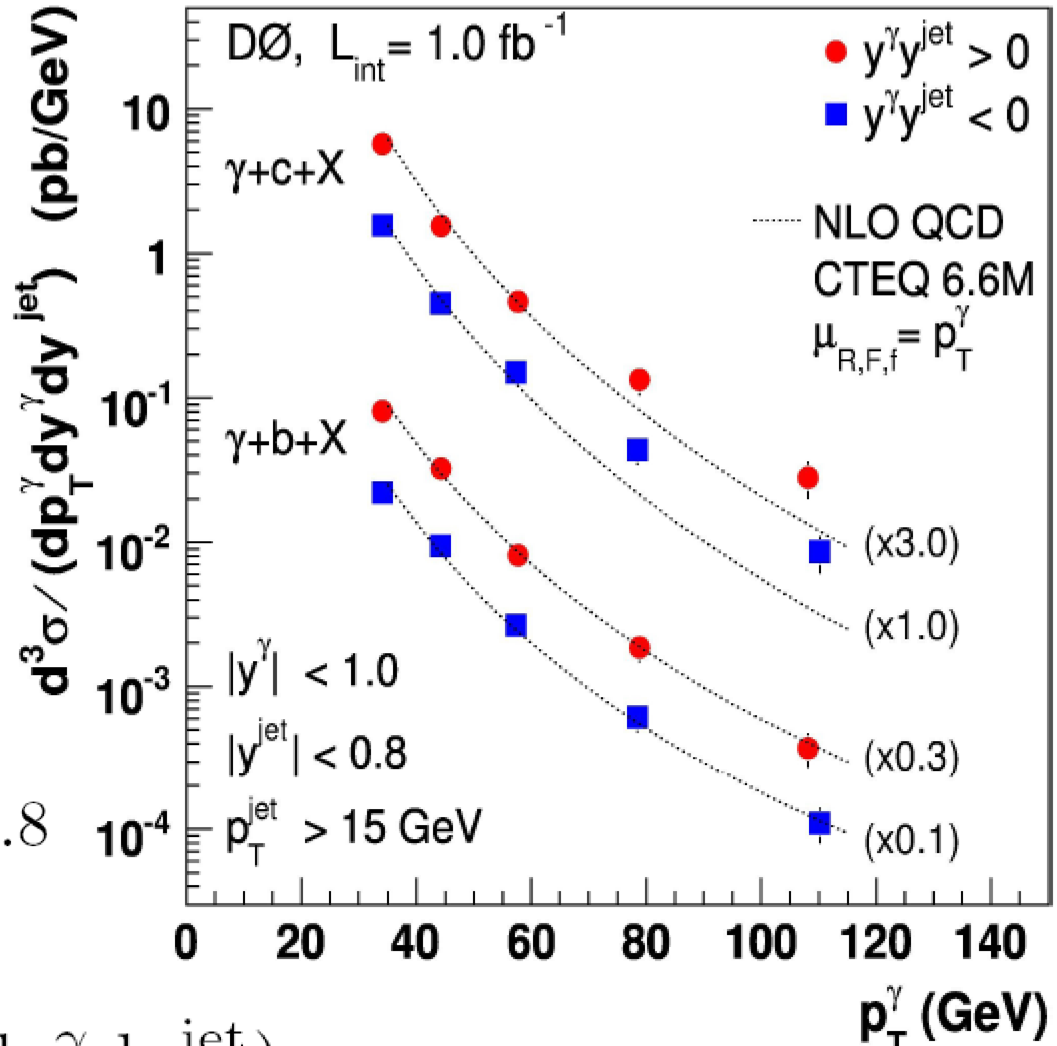
→ test gluon splitting contribution

tag **photon and jet**

Rapidities: $|y^{\gamma}| < 1.0 \quad |y^{\text{jet}}| < 0.8$

→ triple differential $\mathrm{d}^3\sigma/(\mathrm{d}p_T^{\gamma}\mathrm{d}y^{\gamma}\mathrm{d}y^{\text{jet}})$

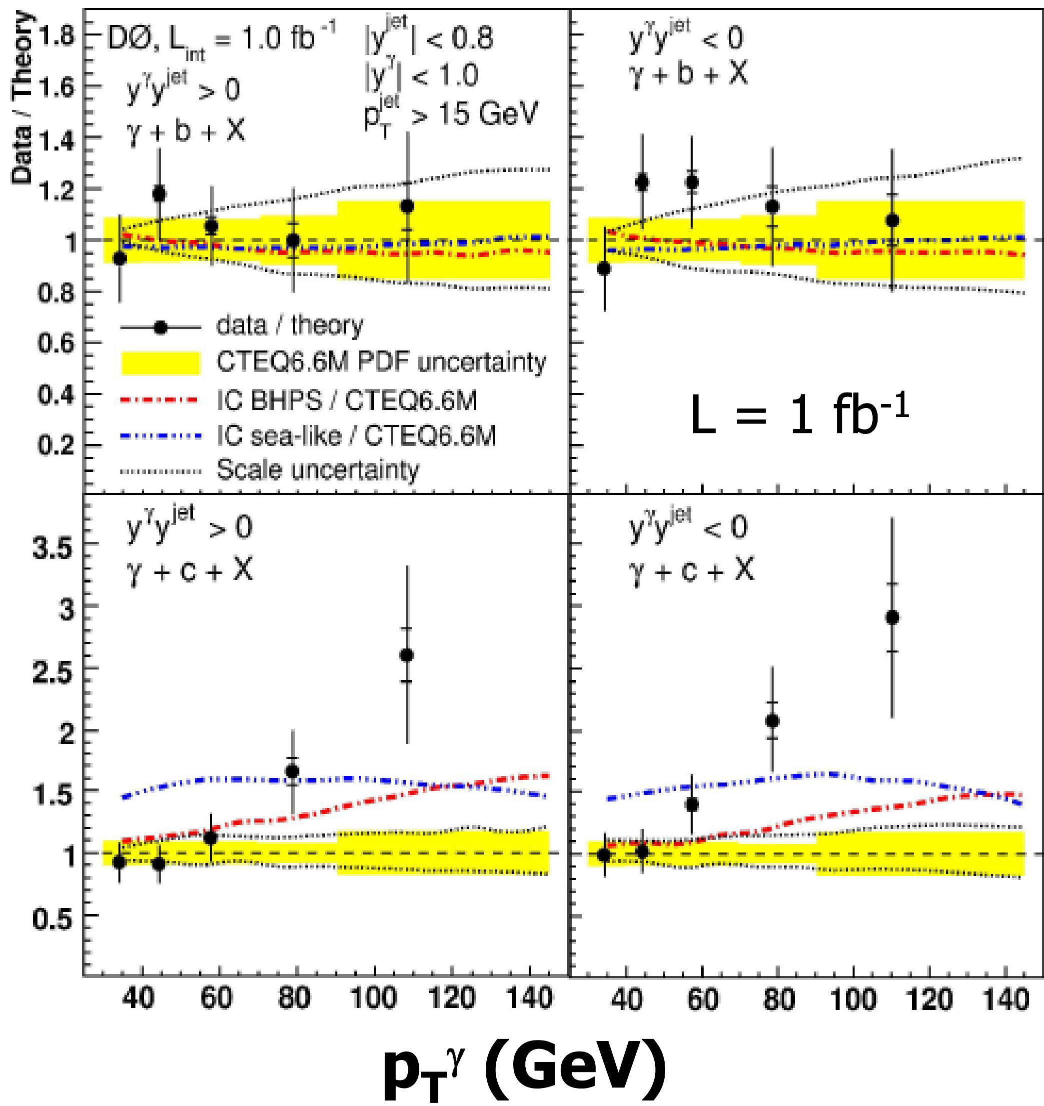
Phys. Rev. Lett. 102, 192002 (2009)



Isolated Photon + HF Jet

→ photon+b:
agreement over full
pT range: 30-150 GeV
→ no PDF sensitivity

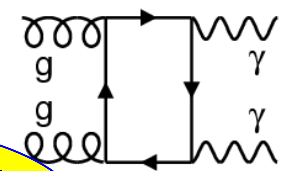
→ photon+c:
- agree only at pT<50GeV
- disagreement increases with photon p_T
- using PDF including intrinsic charm (IC) improves the theory p_T dependence

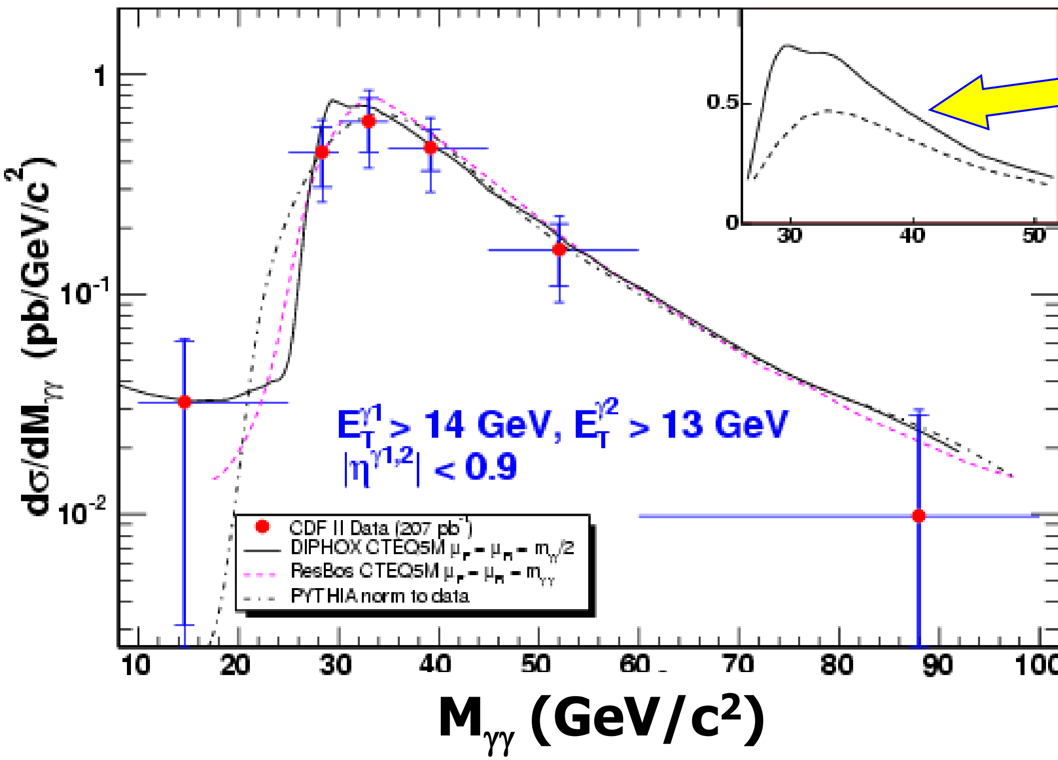


Di-Photon Cross Section

CDF Collab., Phys. Rev. Lett. 95, 022003, 2005. (207pb-1)

- Pseudorapidity < 0.9
- Photon pT> 13 & 14 GeV

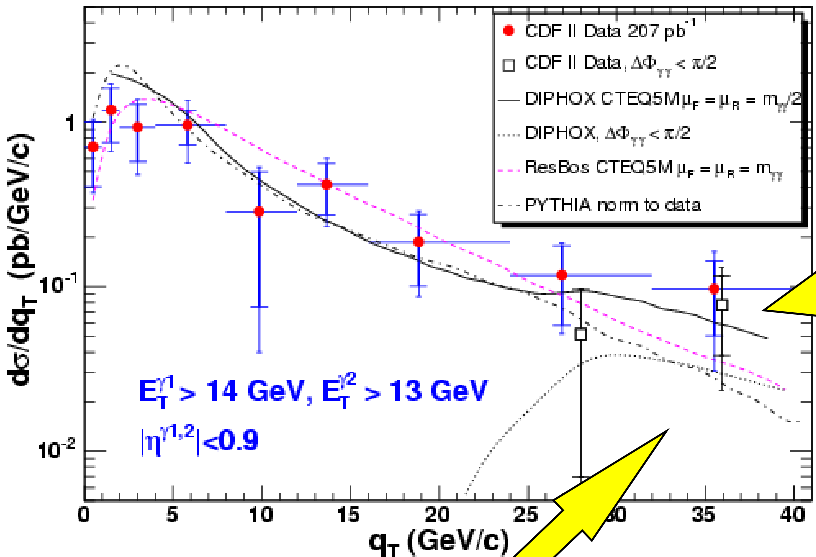


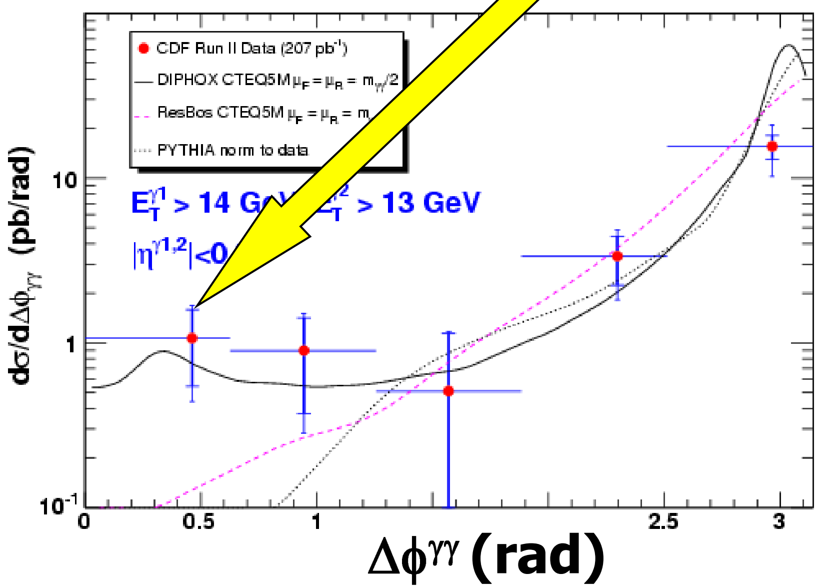


DIPHOX: with and w/o NNNLO gg-diagram

- **DIPHOX**:
  - NLO prompt di-photons
  - NLO fragmentation (1 or 2 γ)
  - NNNLO gg→γγ corrections
- **ResBos**:
  - NLO prompt di-photons
  - LO fragmentation contribution
  - Resummed initial state gluon radiation (important for qT)
- **PYTHIA** (increased by factor 2)

Di-Photon Cross Section





Additional measurement for $\Delta\phi$ (gamma-gamma) < $\pi/2$ (open markers) compared to DIPHOX

- NLO fragmentation contribution
  - only in DIPHOX
  → at high qT, low $\Delta\phi$, low mass

- Resummed initial-state gluon radiation – only in ResBos → at low qT

<u>Important:</u>

need combined calculation with NLO fragmentation & initial state resummation